Spatial Informatics Final Report

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Title—Optimal Trajectory Planning for a Mars Rover Using Spatial Data collected by Mars Orbiters

Description—This project aims to plan an optimal trajectory for a rover traveling between two selected sites. The rover trajectory is optimized by considering terrain difficulty, obstacles, and energy consumption constraints.

Problem Definition and Final Objectives

The problem is defined through the description and the objectives that follow in this report. There are several objectives that I aim to achieve. These are listed below.

1. Find and establish a suitable CRS for Mars. (CRS = Coordinate Reference System)
2. Find necessary data and extract out useful information from them.
3. Using a DTM of a particular region of Mars, find a suitable movement directions given a start point based on only the slope data.
4. Using the movement directions and the slope data, establish a means of finding a least cost trajectory given a start point. This establishes a good base over which I can put more constraints.
5. List down all the spatial methods used for the same.
6. Process more data similar to the slope data to add more constraints to the path optimisation problem.
7. Inculcate danger zones – deep craters, big rocks.
8. Make local slope analysis (limit the rover to a maximum slope of 30 degrees and max rock encounter to 2 * diameter of the wheels)
9. Streamline into a pipeline.
10. Make a 3D surface visualiser to make the robot traverse it (like a game).

I. ASSUMPTIONS OR CRITERIA

A. Assumptions on Landing Sites

Criteria for landing sites include

a. low slope
b. minimal elevation changes
c. proximity to water ice deposits
d. scientific interest

Scientific interest refers to the proximity to important artifacts like ice deposits, important rocks and craters.

B. Assumptions on Rover Path

The path the rover for which this trajectory is being computed is subject to the following assumptions:

The rover must avoid:

a. Steep slopes
b. Obstacles (rocks and craters)

It should minimise the energy consumption as well. This includes not only travelling on least cost paths but also maximizing solar exposure. Data about solar exposure is given by Mars Odyssey THEMIS (details in the section on data)

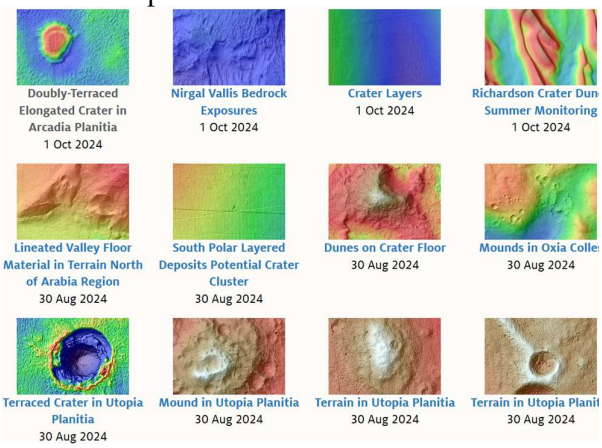
C. Assumptions on Precision

The extent to which we are capable of estimating the trajectory precisely is dependent on the data publicly available from Mars missions. The ones with the highest resolution (like HiRISE) are limited to 1 meter at most places. This would be the limit when calculating the trajectory.

D. Assumptions on Extent and Extensibility

While it is possible for calculating the trajectory of all of the places on Mars, the data for the entirety of the Martian surface is not available and hence given any two random points, we would be able to generate the trajectory only if all data is present. For example the data is usually cantered around specific areas of interest.

Here is an image, showing that the data is only available in parts to us:



II. DATA – SOURCE, CHARACTERISTICS

In this section, I will describe the data I am using for the purpose of the project. I will also describe the source and characteristics of each type of data I am using.

A. MOLA (Mars Orbiter Laser Altimeter)

Source: MOLA data was collected by NASA's Mars Global Surveyor, which orbited Mars from 1997 to 2006.

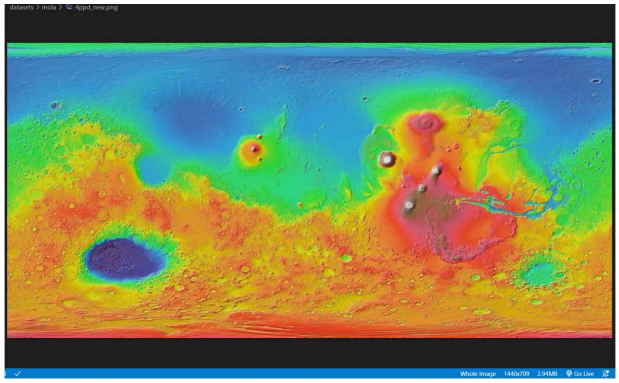
Characteristics:

1. **Purpose**: Provides highly accurate elevation and topography data for Mars, essential for understanding the planet's surface structure and geological features.
2. **Data Type**: Altimetric data, which measures the time it takes for a laser pulse to travel from the orbiter to the planet's surface and back. This creates a detailed digital elevation model (DEM).
3. **Resolution**: MOLA data has a vertical accuracy of about 1 meter and a spatial resolution of approximately 100 meters in low-lying regions, allowing scientists to visualize large-scale terrain features as well as smaller details.
4. **Applications**: Used extensively for topographical mapping, geological analysis, and to support landing site selection by identifying safe, level areas for Mars missions.

Limitations:

1. **Resolution Constraints**: Although detailed for large-scale mapping, MOLA's resolution (100 meters per pixel) is too coarse for identifying small-scale features critical for landing site or rover navigation, such as boulders or fine terrain variations.
2. **Data Gaps**: MOLA provides limited data on steep terrains like cliffs and crater walls, where laser returns are either unreliable or missing due to the angle of incidence.

Here is the MOLA dataset which I extracted and georeferenced from the official website at 4PPD: (Colorized Elevation Map)



B. HiRISE (High-Resolution Imaging Science Experiment)

Source: HiRISE is a camera on board NASA's Mars Reconnaissance Orbiter (MRO), which has been orbiting Mars since 2006.

Characteristics

1. **Purpose**: Captures extremely detailed surface imagery of Mars, allowing identification of surface features such as craters, rocks, and obstacles. It's especially valuable for landing site assessments and geological investigations.
2. **Data Type**: High-resolution optical images, including both grayscale and color imaging.
3. **Resolution**: HiRISE has a spatial resolution of up to 0.25–0.3 meters per pixel, one of the highest resolutions available for Mars imagery, providing detailed views of the surface and small features.

Note: I am using a resolution of 1 meter per pixel.

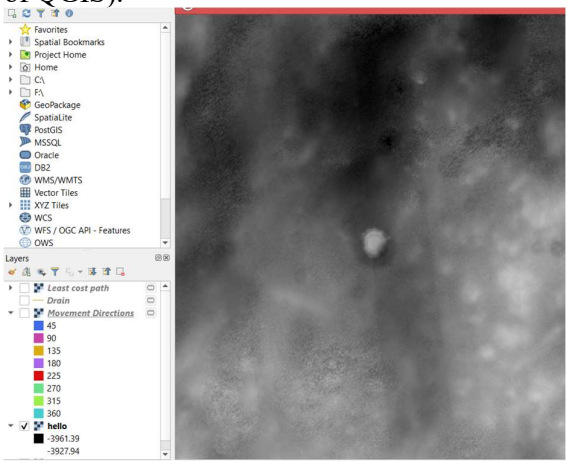
Limitations

1. **Limited Coverage**: HiRISE can only image a small portion of Mars at high resolution due to storage and transmission limitations, covering less

than 3% of the planet's surface. This restricts its use to targeted areas of scientific interest.

2. **High Data Volume**: The high-resolution images generate massive data files, making it time-consuming to process and analyze, especially when generating 3D models from stereo images.
   This is an issue which I faced, and it was very time-taking to generate even small trajectories.
3. **Lighting and Atmospheric Conditions**: Dust storms and seasonal lighting changes can reduce image quality, affecting visibility of specific features or areas during certain times of the Martian year.

This is the HiRISE data which I used (view of QGIS):



C. CRISM (Compact Reconnaissance Imaging Spectrometer for Mars)

Source: Mars Reconnaissance Orbiter, operated by NASA, with data accessible via JHU APL CRISM website.

Characteristics:

- **Purpose**: Locates minerals and identifies regions of interest for signs of water or volcanic activity.
- **Resolution**: 18 meters per pixel in high-resolution mode, 200 meters per pixel in mapping mode.

Limitations:

- **Data Quality and Noise**: CRISM hyperspectral data is susceptible to noise, especially in low-light or dusty conditions. Some wavelength channels may contain noise, which complicates accurate mineral identification.
- **Limited Spatial Coverage and Seasonal Biases**: Due to limited data storage and transmission capacities, CRISM only maps portions of Mars, with priority given to high-interest areas. Its spectral imaging is not uniform across all seasons, so temporal analysis for seasonal changes may be challenging.

Here is an image of the carbonate deposit as seen from CRISP.

III. Spatial / Spatio-Temporal Methods used

I have mostly used Spatial methods for the purpose of the mid-submission.

They are listed as follows:

- Raster Reprojection
- Georeferencing
- Cost Surface Analysis - Cumulative Cost Mapping
- Cost Surface Analysis - Movement Direction Mapping
- Spatial Extent Definition
- Least-Cost Path Analysis
- Segmentation

- Overlay Analysis
- Morphological Operations
- Thresholding
- Hough Circles
-

Here are these methods written in detail:

1. File Format Conversion (GDAL)

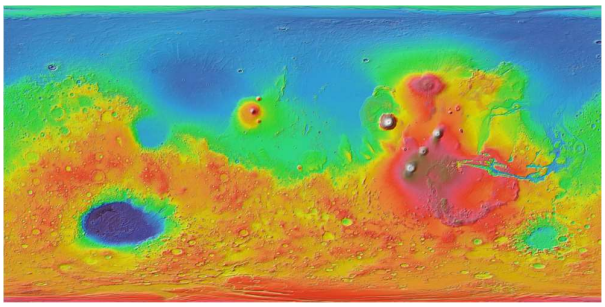
- **Method**: $gdal\_translate$
- **Usage**: Converted the original $.img$ file from the HiRISE dataset to a .tiff format. This conversion ensures compatibility with QGIS and certain tools. It prepares the data for further analysis by making it accessible in different software environments.

1. **Georeferencing**
   - **Method**: Georeferencing in GIS
   - **Usage**: Assigned real-world geographic coordinates to the raster image, ensuring it aligns with a coordinate system ($MARS$ 2000). This step is critical for spatial accuracy, allowing the image to be integrated with other spatial layers and enabling precise spatial analysis.
2. **Cumulative Cost Surface Calculation**
   - **Method**: $r.walk.rast$ (from GRASS GIS toolbox in QGIS)
   - **Usage**: Used this tool to generate a **cumulative cost surface**. This process calculates the accumulated "cost" of movement across the landscape from a starting point, considering the slope factor only (for now, will add more in final submission). The resulting raster represents the total cost of travel to each cell, which is vital for analyses that consider movement or accessibility across a region.
3. **Movement Direction Mapping**
   - **Method**: $r.walk.rast$ (continued)
   - **Usage**: Alongside the cost surface, $r.walk.rast$ also computes **movement directions**. This raster indicates the direction of travel from each cell to its least-cost neighbouring cell. It provides a flow direction map, which can be used to model movement, water flow, or other directional processes.
4. **Spatial Extent Specification**
   - **Method**: GRASS region extent
   - **Usage**: Defined the spatial extent (the area of interest) for the analysis by specifying a **GRASS region**. This step limits the analysis to a specific region of the raster, improving efficiency and focusing the study area on regions of relevance while reducing computational overhead on the entire dataset.

     I did this because the HiRISE dataset for even a small region is huge, and it was theoretically taking many hours to calculate the entire least cost line.
5. **Least-Cost Path Analysis**
   - **Method**: $r.drain$ (from GRASS GIS toolbox)
   - **Usage**: Isolated a small region within the larger dataset and applied **least-cost path analysis** to identify the optimal route from a starting point to a target location. This tool traces the path that incurs the least cumulative cost, based on the previously calculated cost surface, which can represent the most efficient path for movement, resource transport, or ecological corridors.
6. **Map Segmentation**
   - **Method**: Area segmentation (manual selection)
   - **Usage**: Focused the analysis on a smaller segment of the raster by selecting a specific area of interest. Segmentation helps isolate regions, making the analysis more manageable and ensuring that the pathfinding and cost calculations are concentrated where they are most relevant.

Initial Results

A. MOLA dataset and problems with it



This is the mola dataset for the relief map is constructed.

This is good for getting a rough idea of the vertical elevation around a large enough area, highlighting important features. However, some calculations show that using this is not favourable for the planning of a trajectory for a mars rover.

MOLA dataset is available in PPD (= Pixels per Degree)

$$Circumference\ of\ Mars\ (C) = 2\pi r$$

$$C = 2\pi \times 3{,}396{,}000 \approx 21{,}341{,}000\ meters$$

$$Distance\ per\ Degree = \frac{C}{360} \approx \frac{21341000}{360}$$

$$\approx 59216.67\ metres$$

Converting PPD to Meters per Pixel

$$Metres\ per\ pixel = \frac{Distance\ per\ degree}{PPD}$$

$$= \frac{59216.67}{n}$$

The highest resolution available is 512 PPD

$$Meters\ per\ pixel = \frac{59216.67}{512}$$

$$\approx 115.7\ metres\ per\ pixel$$

This is because even with the highest resolution of 512 PPD, we still have about 115.7 meters per pixels which is very large.

Also, for practical maps of 4PPD resolution, there is no way we can do any meaningful calculations for the trajectory estimation.

Adequate map for usage on home systems is 4PPD or 8PPD if we are considering entire map

$$Meters\ per\ pixel = \frac{59216.67}{4}$$

$$\approx 14804\ metres\ per\ pixel$$

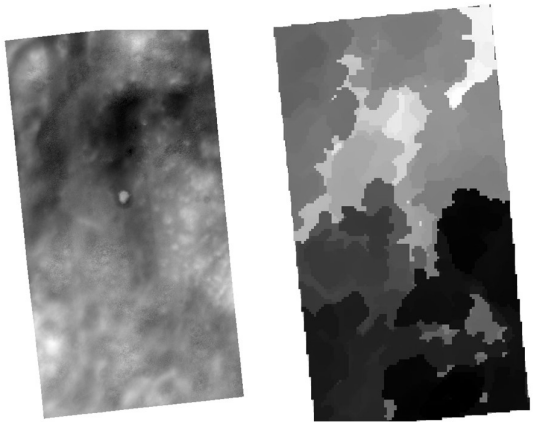
We clearly see that we cannot use the MOLA dataset for precise trajectory calculations.

B. Switch to HiRISE dataset

As shown in the calculations in the last section, we cannot use the MOLA dataset for the trajectory calculation. We have to instead use a High Resolution dataset. HiRISE comes into play here.

I extracted the **Doubly-Terraced Elongated Crater in Arcadia Planitia** DTM from the HiRISE datasets.
In QGIS,

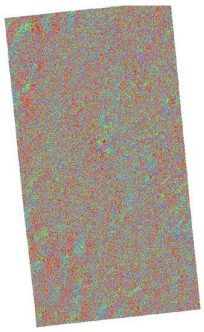
a) Cumulative Cost Map



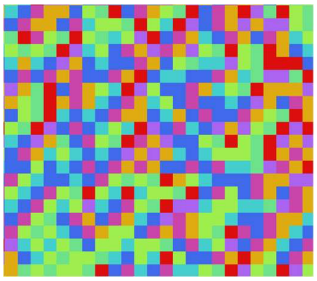
Legend

cum_cost_50
-2.06109e+09
-3.1212e+07

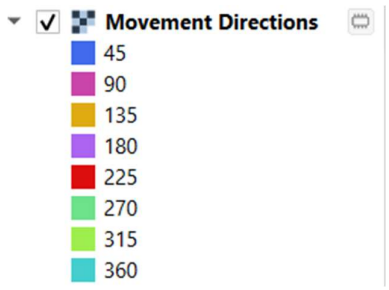
a) **Movement Directions**



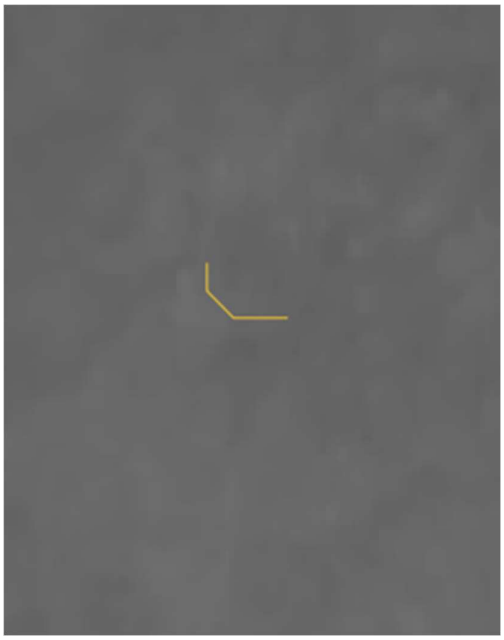
Mosaic of movement directions



Legend



b) **Least Cost Path within a limited region**



Computed using $r.drain$ for a small region for proof of concept. Larger regions require much more time. There are about 3250 pixels in this region.

**Contributions during final submission start from the next page

I. Contributions to Final Submission

I have made the following contributions after the mid evaluation to the project and have obtained promising result.

Here, I list down all the tasks completed.

1. Implement a custom algorithm to find the shortest path from a start point and an end point.
1. Include checks and route the rover away from danger zones. Inculcate danger zones – deep craters, big rocks.
2. Affinity points: Include "via" points which need to be visited however from a distance. E.g. Craters, ice deposits, etc.
3. Inclusion and processing of the CRISM dataset. This includes identification of high concentration of ice deposits using image processing of a raster. This includes thresholding, morphological operations and Hough Circles.
4. 3D visualiser for the HiRISE dataset with the path overlayed in 3D.
5. A simple robot that traverses the terrain.
6. *Accounting for local slope gradient. E.g. if the rover has a physical constraint of a tolerance of 30 degrees to climb a slope, it would only follow a trajectory that satisfies this constraint.

II. Implementation of the Path Planning Algorithm

A. Gist of the implementation

A DTM is a raster whose each pixel holds a value / some values. Usually the first (and only) value is the elevation of a point on the DTM.

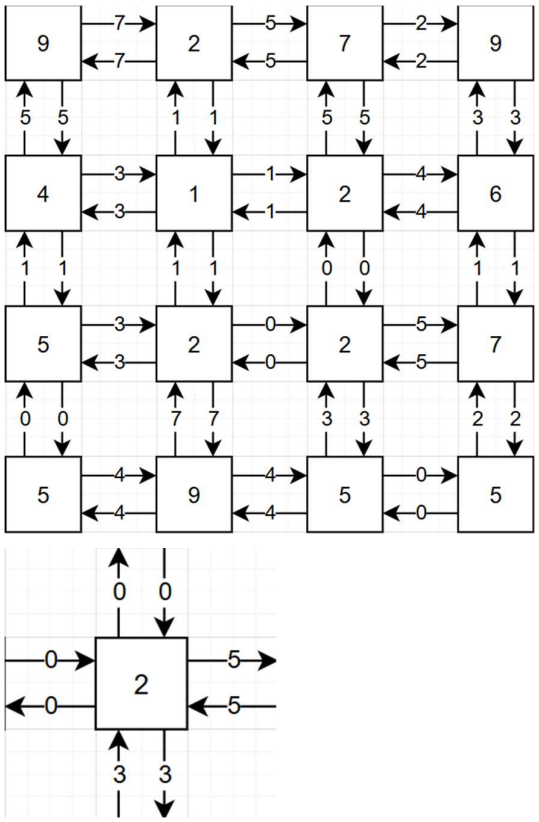
High Resolution DTM are larger. Large enough that it theoretically takes my machine about thirty minutes to generate a brute-force graph (using pairs) for a $70\ m * 70\ m$ area on the Martian surface.

This brute force method makes large scale computation slower but gives the same accuracy with the method I am going to describe here.

The idea is to implement a dense graph of the same size as the DTM however with a different shape.

If the shape of the DTM is (n, m, 1) which means the raster is of size $n * m$ and has 1 value at each pixel, the shape of the dense graph that would be used to find the path would be of shape $(n, m, 5)$, the three more values account for the cost of the edges emerging from the node to the nodes on the left, the top, the right and the bottom.

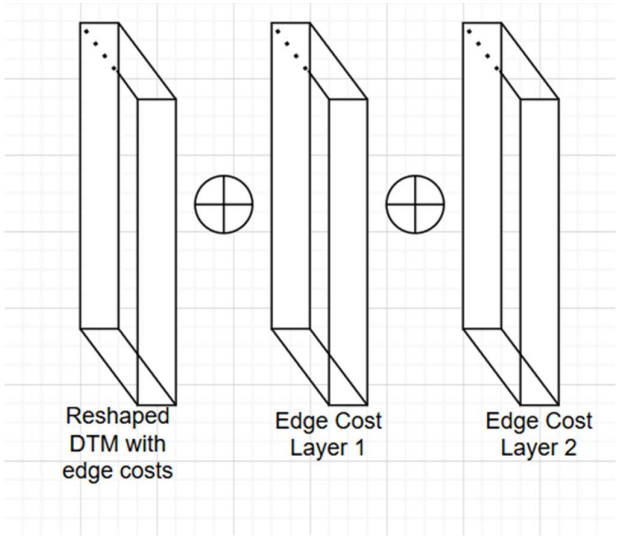
Here is the visual representation of the graph



[2's tuple would have 5 values: 2, 0, 5, 3, 0]

The edge weights are initially computed by the absolute difference between the heights of two adjacent pixels.

Later, because the extent dimensions are the same as that of the DTM, any number of "weight layers" can be super-imposed directly to the graph.



Now, having the edge weights and the coordinates, we can calculate the path using a simple Dijkstra's Algorithm implementation since our graph would always have a non-negative value of edge weights as can be deduced from the implementation.

This effectively reduces the complexity from $O(n^4 - n^2)$ to $O(n^2)$.

B. Avoiding danger zones

To avoid any regions that we wish not to visit, we can overlay another layer in a vectorised way to the existing weights layer.

The idea is to have a weights layer that has infinite weights near to the danger zone and gradients out.

I show this with the implementation in the illustrations section.

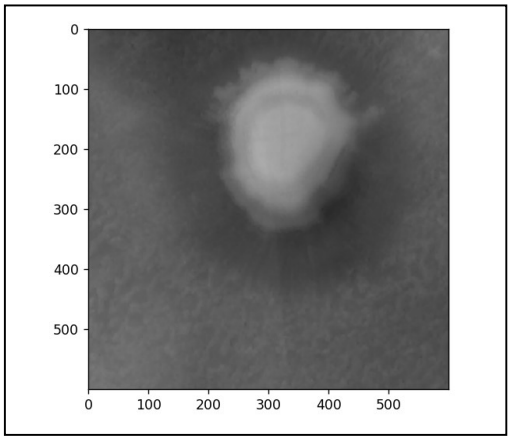
C. Affinity Points

We may want our mars rover to go near to certain regions especially to regions like ice deposits. This feature has been implemented and can be seen in example in the illustrations section.

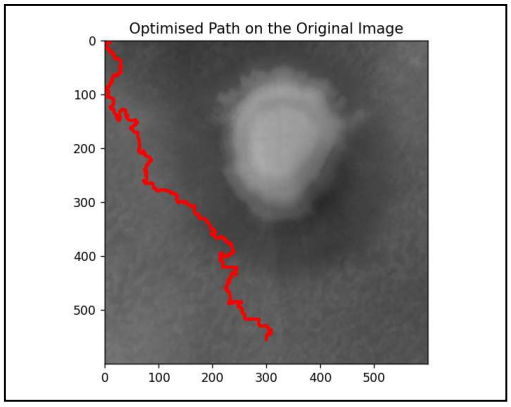
The dataset CRISM gives many such important points of scientific interest. After these points have been identified, they can be overlayed as described about.

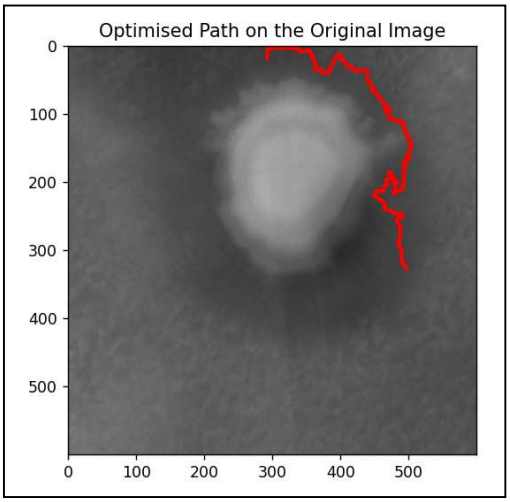
III. Illustrations of the Algorithm

1. Base Image

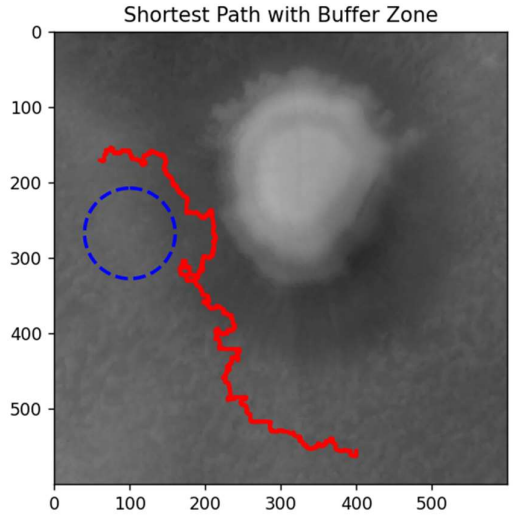


2. Planned Path between two given points.



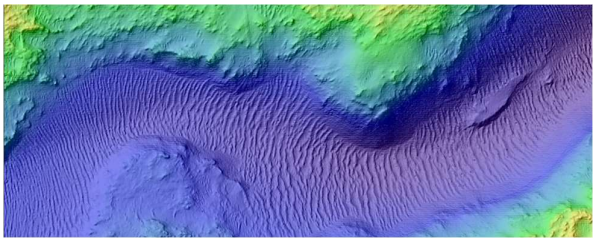


Another demonstration with different start and end points.

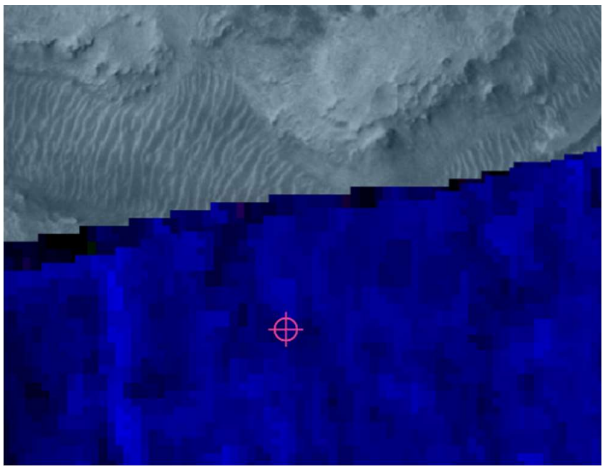


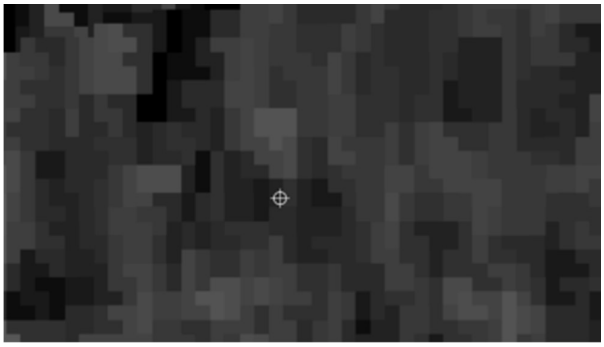
IV. Processing of CRISM Dataset Using Image Processing.

Let us look at this beautiful picture of a region in mars at the coordinate location of $18.69° \; LAT, 78.15° \; LON$



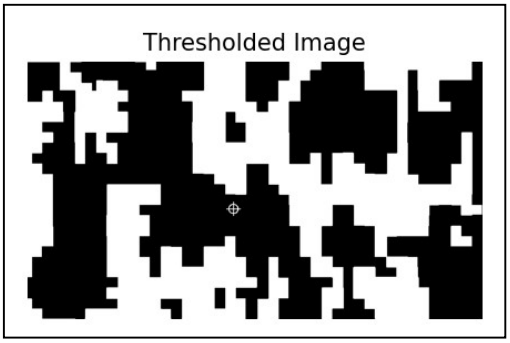
Here is an example of the amounts of ice deposits in the area:



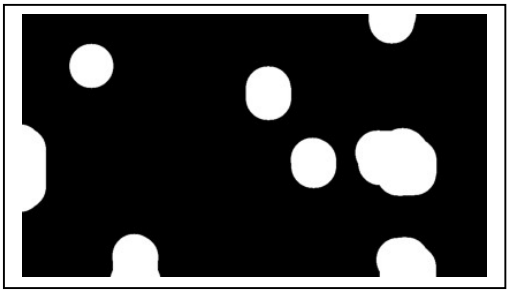


We apply concepts of image processing to get the regions of interest here which we would like our Mars rover to traverse to.

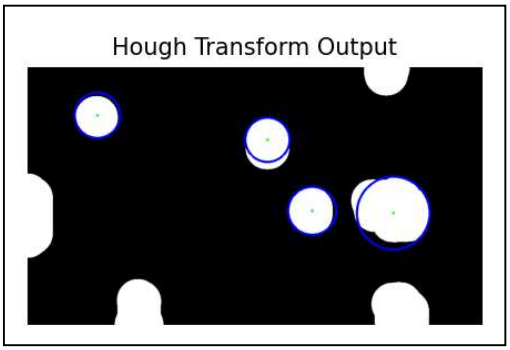
1. Image Thresholding



2. Morphological Operation: Closing



3. Hough Circles to get the coordinates



Output:
>>> The number of circles is: 4

Center location for circle 1: (np.uint16(520), np.uint16(157))
Diameter: 96

Center location for circle 2: (np.uint16(793), np.uint16(316))
Diameter: 158

Center location for circle 3: (np.uint16(617), np.uint16(311))
Diameter: 104

Center location for circle 4: (np.uint16(151), np.uint16(104))
Diameter: 98

These points can be later exported and added as a weights layers as mentioned before.

V. 3D Visualiser of the DTM and the Path

Now, we move on to the 3D visualiser of the DTM and the overlayed path on the it.

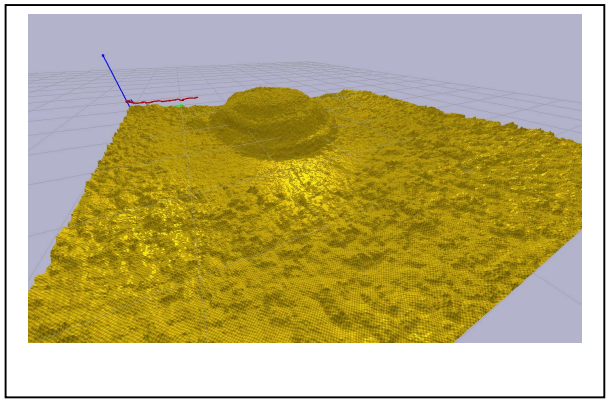
This is the most exciting part for me and it was equally exciting to make this.

I use the library $PyBullet$ for the simulation. From the $.tiff$ file, I generate an image file using Python's $gdal$ library from $osgeo$.

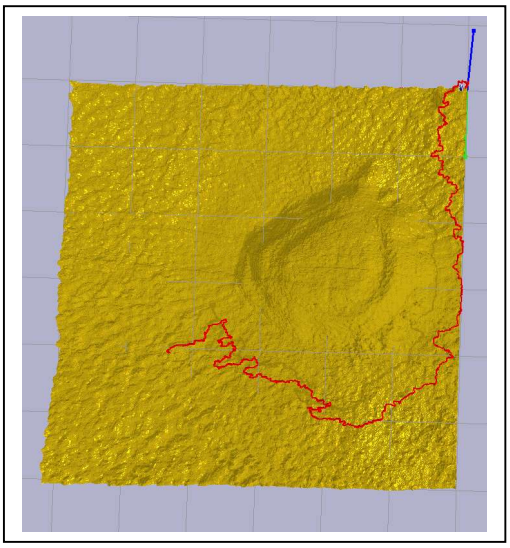
Then I convert this to a $numpy$ array. Further, I use this to extract the elevation values from the DTM.

Then the terrain shape if formed using $PyBullet's$ $createCollisionShape$ method.

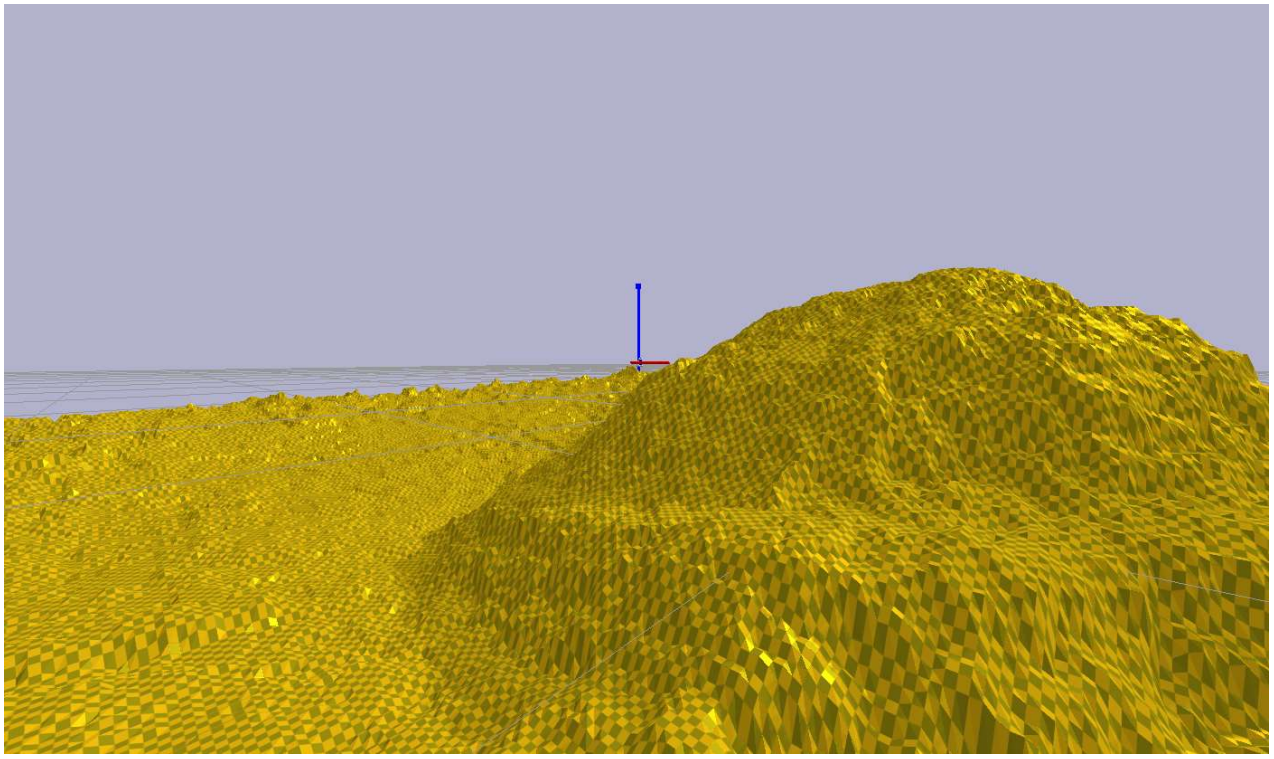
Later, I load the $urdf$ (uniform resource description format) for the robot that should traverse the terrain.



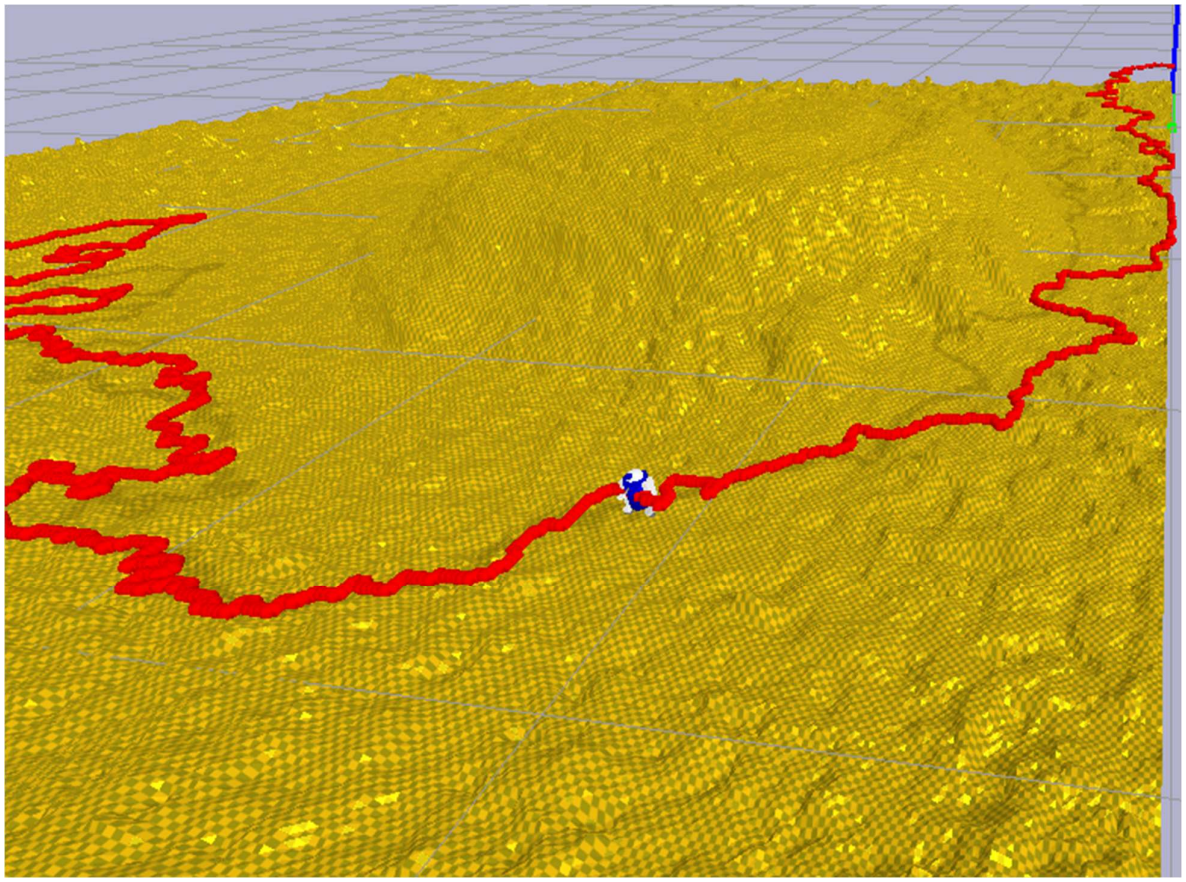
3D Visualisation of the above image using PyBullet



Overlayed path on the 3D visualisation.



Terrain as seen from a different camera view



Robot traversing the path

VI. Special Characteristics

Here, I describe the special characteristics of my approach.

A good chuck of my code is vectorised. This means that it can be parallelised very easily and some load can also be put on a GPU.

This makes it better than some computations done by QGIS which is incredibly slow and does not utilise the GPU.

The 3D visualisation is also fast to generate.

Example of vectorised code written:

```
bottom = np.pad(self.matrix[1:, :, 0], ((0, 1), (0, 0)), mode='constant', constant_values=0)
new_matrix[:, :, 4] = np.abs(self.matrix[:, :, 0] - bottom)  # Difference with bottom neighbor

return new_matrix
```

VII. Limitations

In this section, I discuss the limitations of my work.

1. **Coarseness of data and prone to error**

   The data used for calculating the main trajectory is taken from the HiRISE dataset. This is the highest resolution available to us. However, this is still 1m per pixel, making it hard for small rovers
   to navigate accurately based on the terrain data.

   However, big robots with bigger wheels would have less problems with this.

2. **Slow speed for plotting path**

   The overlayed path on the 3D visualization takes a while to plot because individual elements in the environment are created. This can be reduced by using prefabs.

3. **Inaccurate physics for the Mars rover**
   Due to resource constraints, I was not able to achieve very accurate physics of the rover while it traverses the terrain. Hence, I made the robot make a flyby just over the terrain in a sequential manner to simulate the process.

4. **Only includes raster data**
   My project only includes support for raster data to be included to calculate the trajectory of the rover. Any vector data needs to be rasterized (leading to some possible errors in the process)

VIII. Possible Future Work

There are several possibilities for future work possible in this area. One of them would be to include more data while calculating the trajectory. The existing mechanism can be applied directly for the inclusion of raster data.

Vector data support can also be included as methods to add constraints later and hence can be included in any future work.

In future, more accurate simulation of the mars rover can also be made.

IX. LEARNINGS

The learnings through this project were manifold.
Here I list a few of them:

1. Handson use of real-world databases:
2. Understanding of spatial information on a different planet with different projection system:

   Unlike Earth, Mars uses specialized coordinate systems and map projections tailored to its spherical geometry and orbital characteristics. Gaining an understanding of the principles behind Martian projection systems (Mars2000) was both challenging and fascinating.

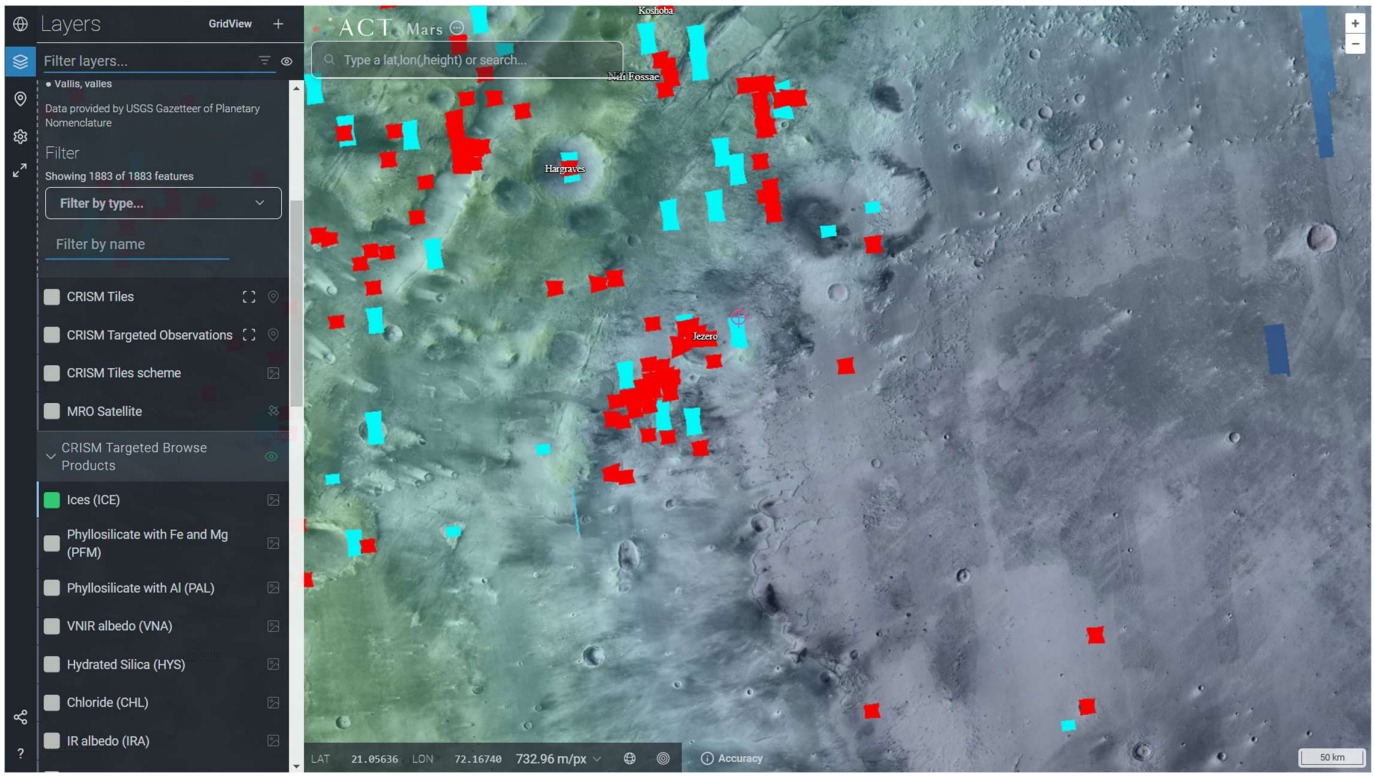
   With this report, I have also attached the learning in the coordinate systems.

3. Making of a 3D visualization from a 2D image.
4. Ability to appreciate the vastness of data in this domain.

X. CODEBASE

My code is hosted on GitHub: https://github.com/anshium/spatial-informatics-project

Appendix: The following website was highly useful for comparing and analyzing the CRISM data



Source: https://mars.quickmap.io/