National Institute for Astrophysics, Optics, & Electronics

Perception, Planning, and Control for Planetary Rovers

Path planning with Digital Elevation Models

MSc. In Science and Technology of Space

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In this example it is shown how to generate a surface given certain characteristics, which include obstacles, as well as certain properties to help us define a cost that depends on different variables, each type of cost is being used to plan a trajectory through the surface in a way that it's the optimum given the different terrain related costs. First, we need a Digital Elevation Model (DEM), which is a representation of a terrain or a topographic surface in which trees, buildings, etc. are excluded. These models are usually generated by information gathered from sensors on satellites, drones and aerial vehicles. We will be using Martian DEMs, which are obtained from the "USGS Astrogeology Provided Analysis Ready Data". This catalogue contains analysis ready data for different celestial bodies, such as the moon, mars, and Europa. The quality and quantity of information for the moon and mars is vast, however for Europa it is still quite low quality, due to those DEM being generated based off of Galileo and the Voyager missions.

With the advent of future space exploration missions focused on Jupiter, we will be able to obtain and utilize new images to generate new and better DEMs to take advantage and perform different types of scientific experiments. After browsing through the USGS catalogue, we find an interesting region that we will focus on. Using a photo visualizer, we can observe the DEM has the shape as shown in figure 1.

Fig. 1 DEM file visualized as a .jpg

We can observe that the image seems to lack detail, however, to manipulate these types of files, specialized software must be used. In this case we will be using "QGIS", a free and opensource geographic information system in which we can manipulate DEM files.

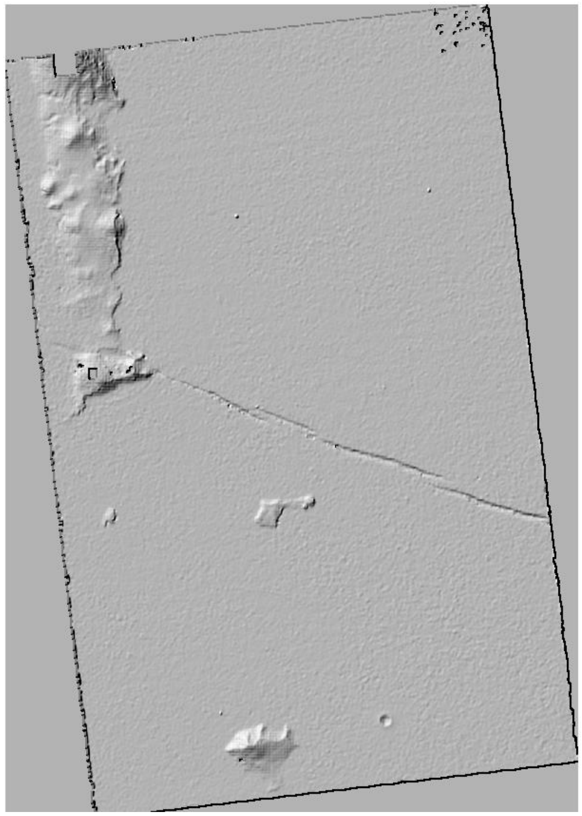

Fig. 2 DEM file visualized in QGIS.

The resolution of the DEM we are working with is of 20m/pixel, to save up on computational resources, we crop the DEM in a way that we only use a portion of the original model, as shown in figure 3. It is worth mentioning that, even though we are experimenting with a real digital elevation model from the Martian surface, there are still a plethora of other external factors that must be considered if one wants to do a more realistic simulation, such as the mechanic characteristics of the terrain or "terramechanics", physical characteristics of the rover such as its mechanic configuration and dynamic model, etc.

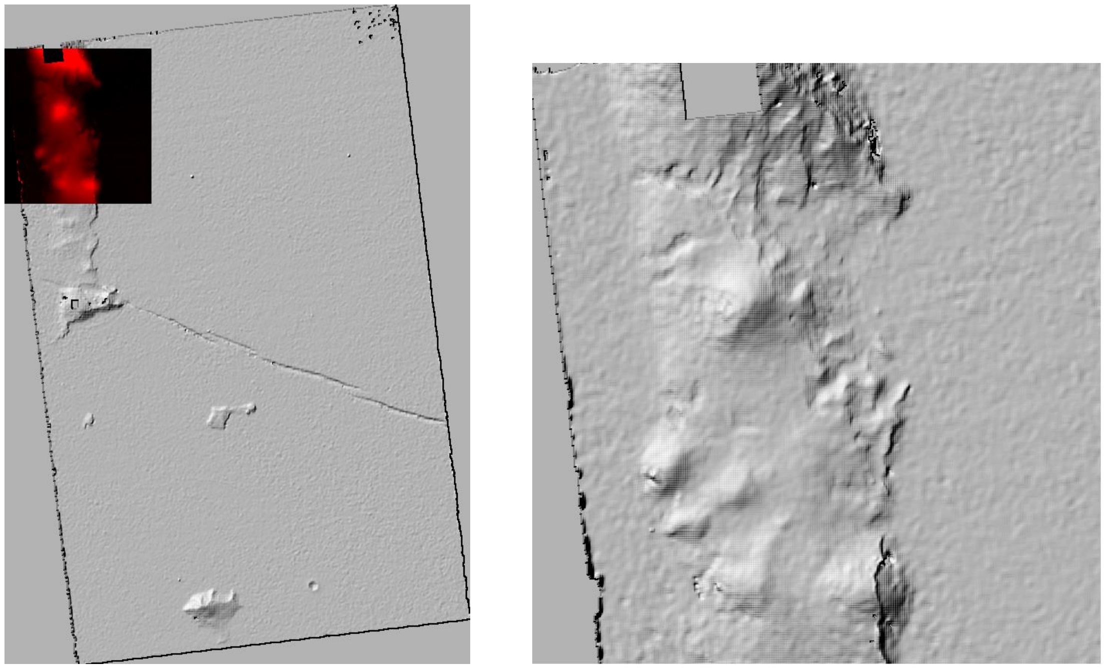

Fig. 3,4 Full DEM file with cropped area in red and black, cropped area visualized on QGIS

We select the specific region from the DEM and crop it so that we use that cropped part of the model for out testing. The cropped section of the model can be seen in figure 4. In figure 5 and 6 a 3D aerial view of the model can be seen as visualized in the QGIS software.

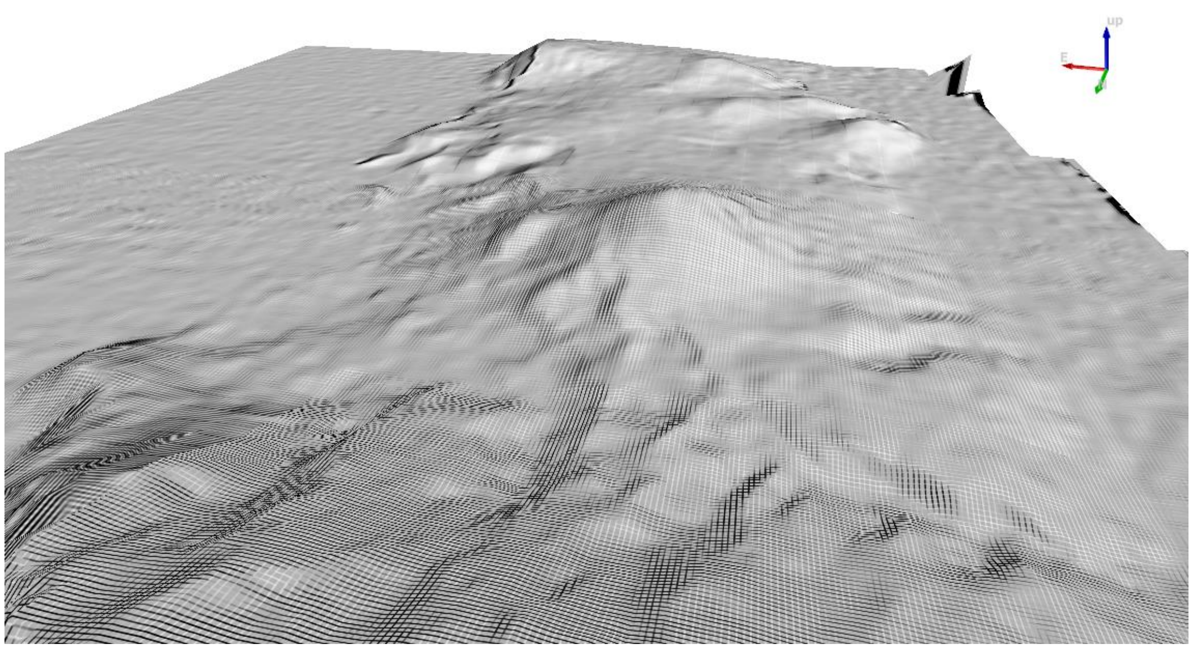

Fig. 5 3D visualization of the DEM file in QGIS

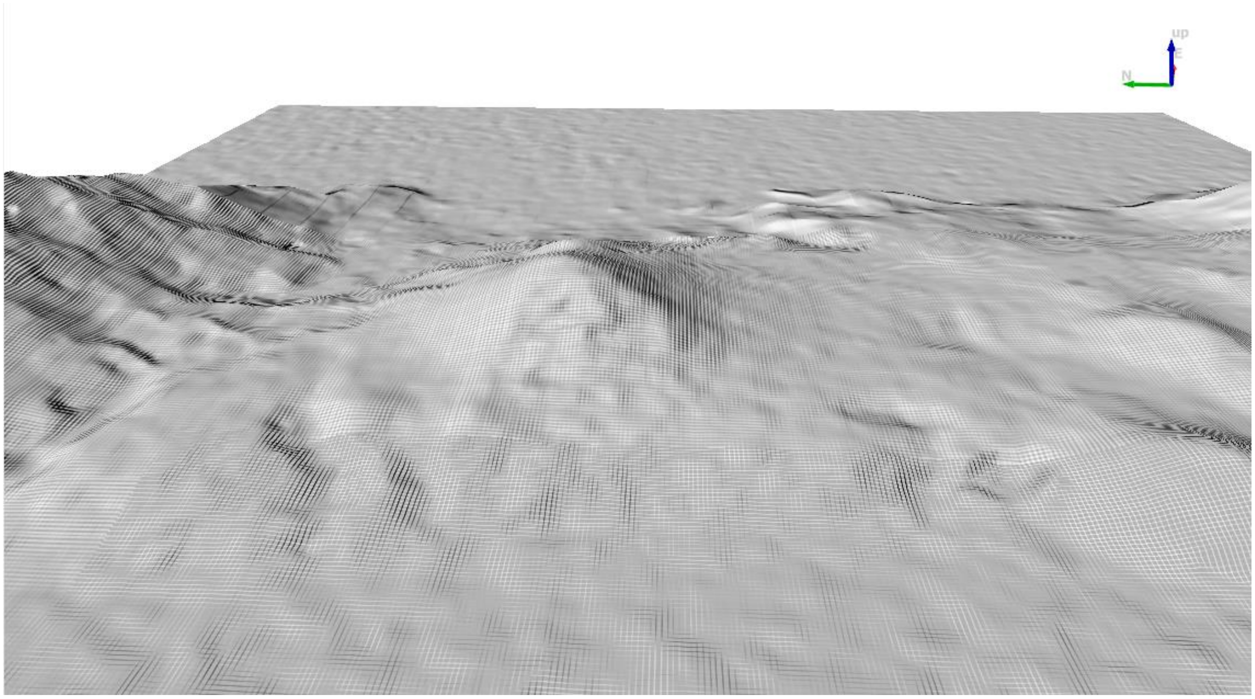

Fig. 6 3D visualization of the DEM file in QGIS

The general architecture of the program is briefly explained and can be visualized in figure 7. First, we obtain our data, be it through a data base or a sensor, in our case, we will be using a database, however, this process can and is most often also done in real time in autonomous robots. After this, we utilize the data obtained to generate the DEM file, from this file we obtain several layers that will be used to make a multi-layer map, from which we generate a custom cost function that takes into consideration different parameters depending on the heuristics for each path planning algorithm. With the resulting trajectories, a simulation in real time is made as well as a final comparison of different metrics.

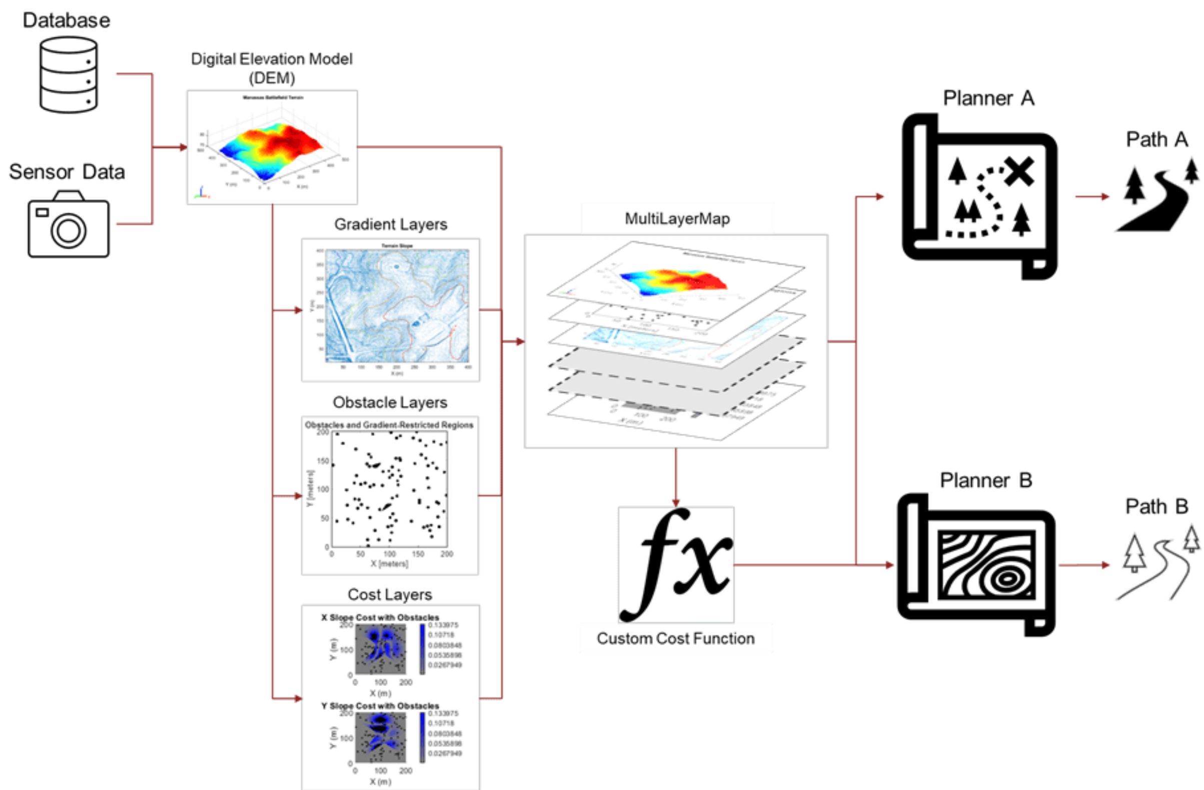

Fig. 7 General architecture of the program

The first step is to decompose the information so that we can visualize the terrain in a three dimensional way, after modifying some lines of code we obtain the next figure, in which we observe the terrain elevations with its respective color gradient. In this terrain we will execute the different path planning heuristics and evaluate each trajectory.

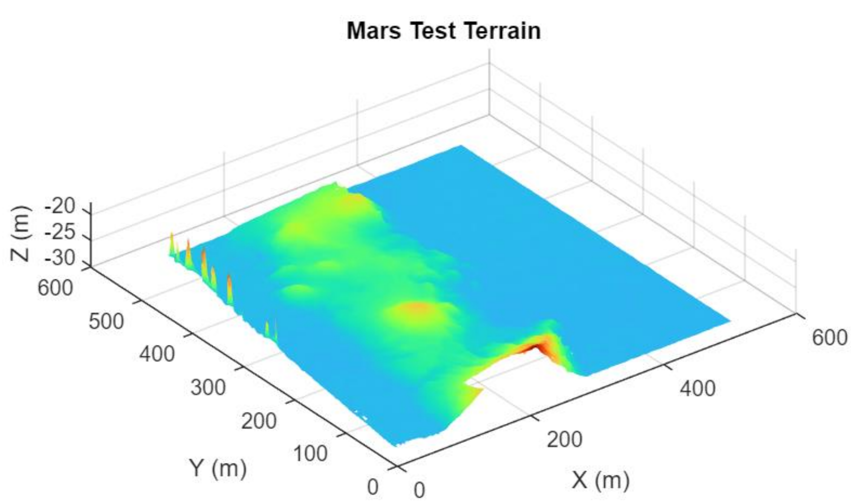

Fig. 8 Visual 3D representation of the Martian terrain

Having this map, we calculate the gradient of the Z layer, which represents the height, assuming cartesian coordinates in $\{x, y, z\}$.

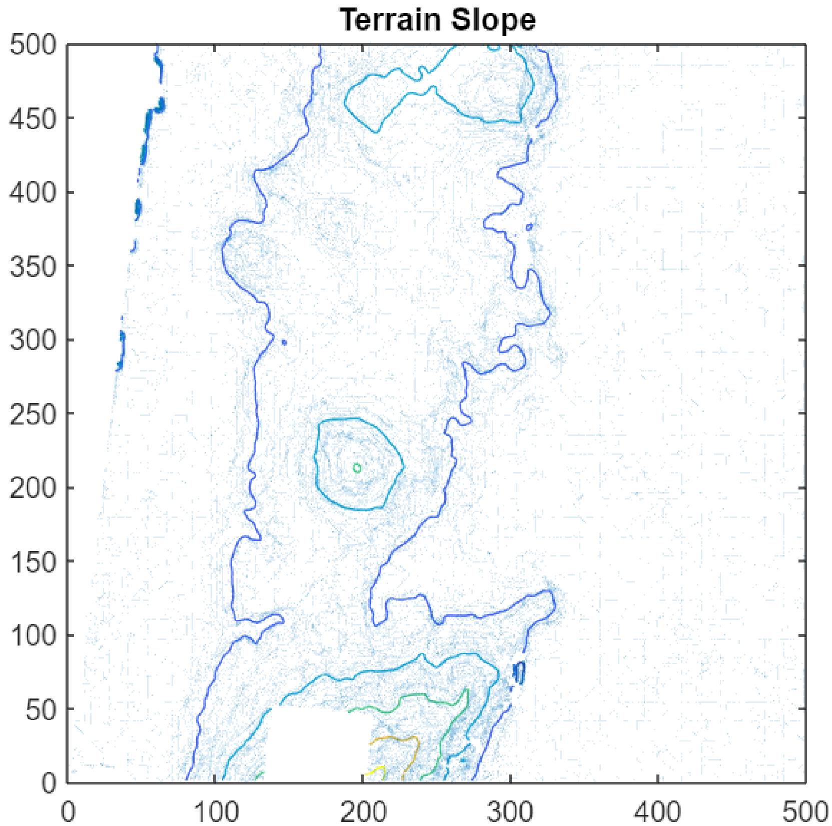

Fig. 9 Contour map that represents the terrain slopes.

From this gradient, a function is defined that translates the value of the gradient into a cost function that scales linearly from $\{0,1\}$, following:

$$C \begin{cases} \dfrac{|m|}{m_{max}}, & 0 \leq |m| \leq m_{max} \\ e^{\left(\frac{|m|}{m_{max}} - 1\right)}, & m_{max} \leq |m| \end{cases}$$

In which

$$m = slope\ angle$$

$$m_{max} = 30°$$

The maximum slope angle is defined by taking as reference the physical capabilities of the Perseverance Rover, which has a maximum slope angle of 45° of tilt, however for safety measures the maximum slope angle is set as 30°. In the next figure we can observe the cost vs slope graph. This is stored in a layer of the multi-layer map for the cost function.

In the program, a randomized binary occupancy grid is added in the digital elevation model, this can be interpreted as rocks or obstacles that impede rover movement.

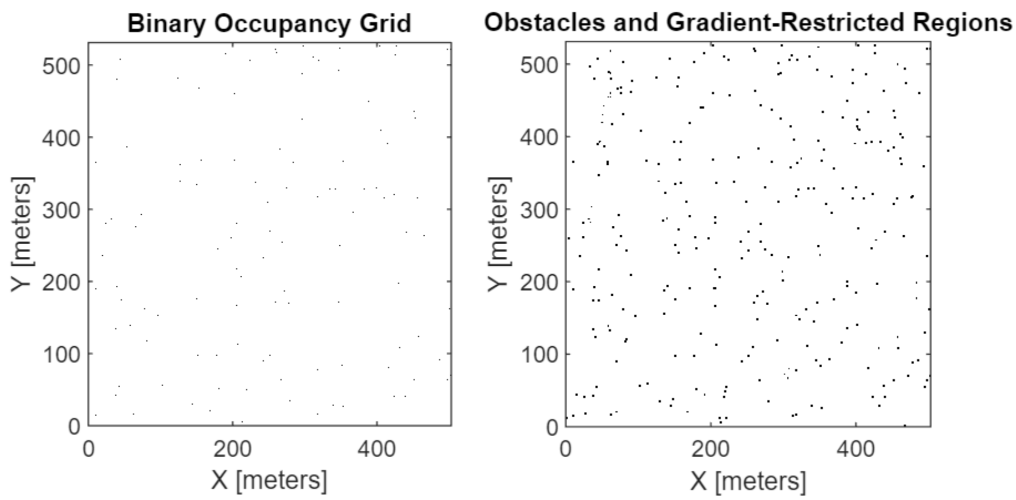

Fig. 10 Graph of the Binary Occupancy Grid, as well as the obstacles and gradient-restricted regions.

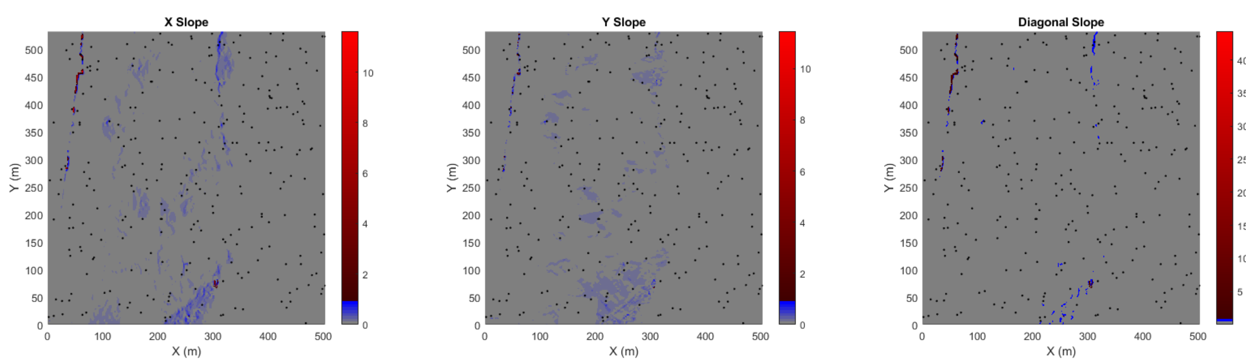

Fig. 11 Visualization of costs based on directional slopes.

In the graphs of figure 12, the colors have different meanings, gray being the terrain is free, blue being costs below a certain threshold and red being above this threshold.

Now the four different methodologies for the path planning algorithms are defined, the first one is based off A*, the other three are explained briefly.

Elevation Aware route

This functional cost considers the actual state of the X, Y coordinates and compares it with the height Z before calculating the distance. This gives as a result the shortest route through a 2.5-dimensional map, balancing the elevation changes against the distance to find the most direct path between two points.

$$C_Z = \|s_2^* - s_1'\|,$$

$$where\ s_i^* = [x_i\ y_i\ z_i * w]$$

Gradient Aware route

This functional cost adds a penalty that scales with the value of the slope in the same direction that the rover is navigating. It doesn't scale with distance; we can assume that it will prefer a longer route with less elevation disparity over a shorter distance path.

$$C_{Slope} \begin{cases} \|s_2 - s_1\| + w * \langle |\widehat{s_2 - s_1}|, |g_x g_y| \rangle & if\ slope < slope_{max} \\ e^{\langle |\widehat{s_2 - s_1}|, |g_x g_y| \rangle} & else \end{cases}$$

Rollover Aware route

Like the previous functional, however the X, Y values of the spatial gradient change, and it penalizes movements perpendicular to the slope, this function minimizes the risk of rollover, preferring routes with lower slope angles.

$$C_{Slope} \begin{cases} \|s_2 - s_1\| + w * \langle |\widehat{s_2 - s_1}|, |g_y g_x| \rangle & if\ slope < slope_{max} \\ e^{\langle |\widehat{s_2 - s_1}|, |g_y g_x| \rangle} & else \end{cases}$$

All the different heuristics for path planning have a variable that adjusts the impact that the functional cost has on the final planned trajectory, the higher this value is, the more impact the heuristic will have on the trajectory and likewise with lowering the value. Certain physical values must be assigned to have a very generic mathematical model of the rover. We adjust the gravity to be in the Martian value, $\sim 3.721 \frac{m}{s^2}$, and assume the rover Mass, maximum velocity, Amps per hour being used, and nominal voltage. We obtain for analysis data on each path planner performance, such as distance, power, travel time, planning time, max pitch, average pitch, max roll and average roll. In the program we obtain an in-real time simulation of the four heuristics travelling through their respective paths.

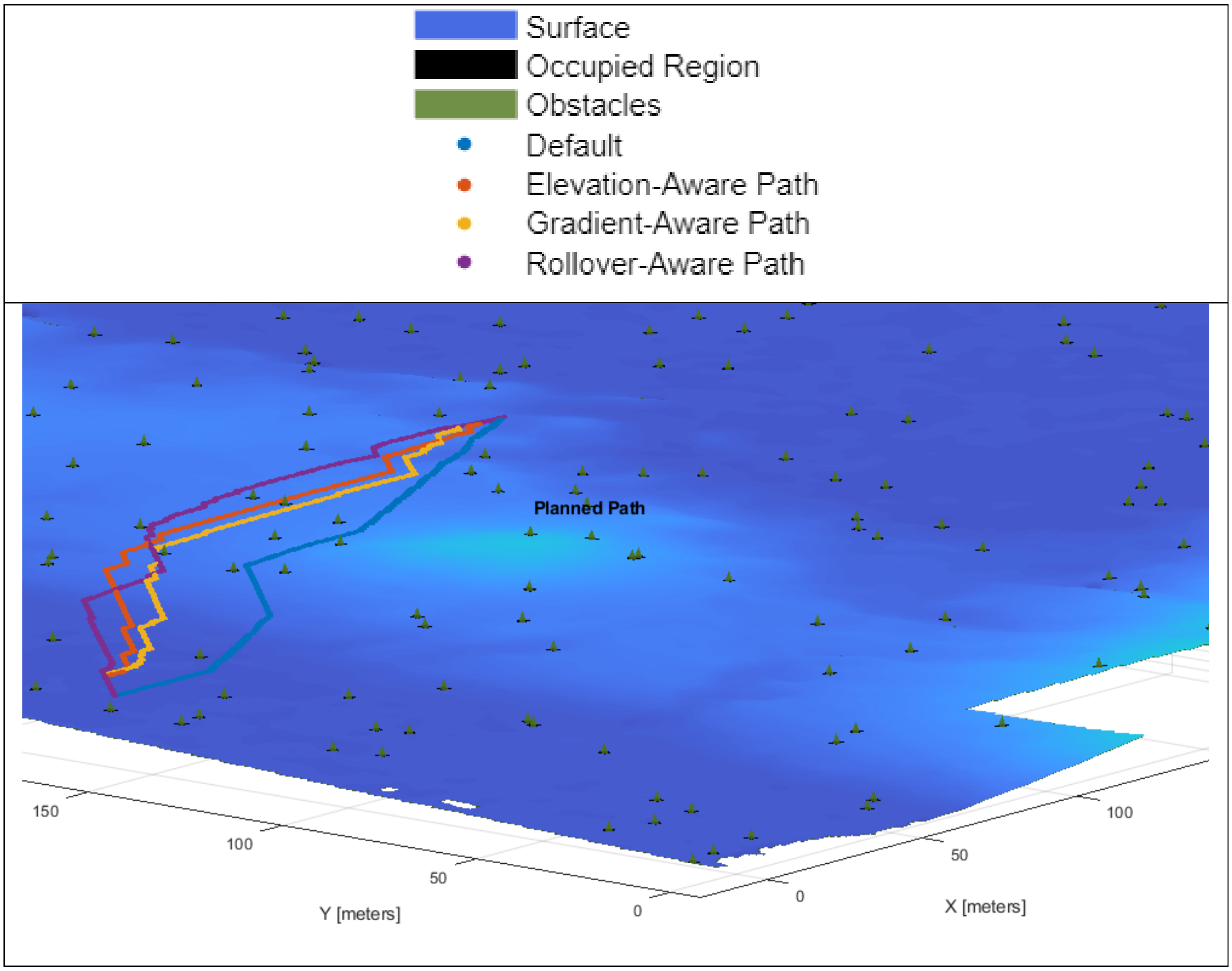

Fig. 12 **Visualization of resulting paths**

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