CS-417 Introduction to Robotics and Intelligent Systems

Planetary Exploration:

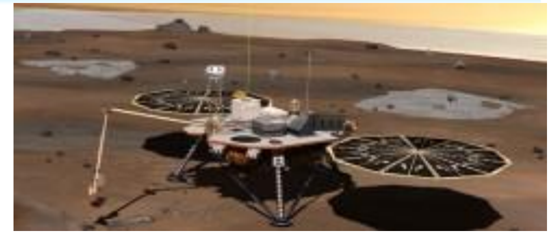
Autonomous Over-the-Horizon Navigation

Ioannis Rekleits

Outline

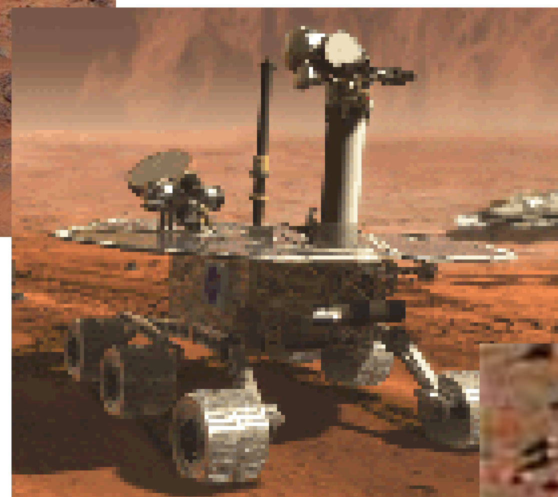
- Mars Exploration
- Background
- Main Blocks are: Terrain Modeling, Path Planning, Motion
- Control Tests from 2006 and 2007

Exploring Mars

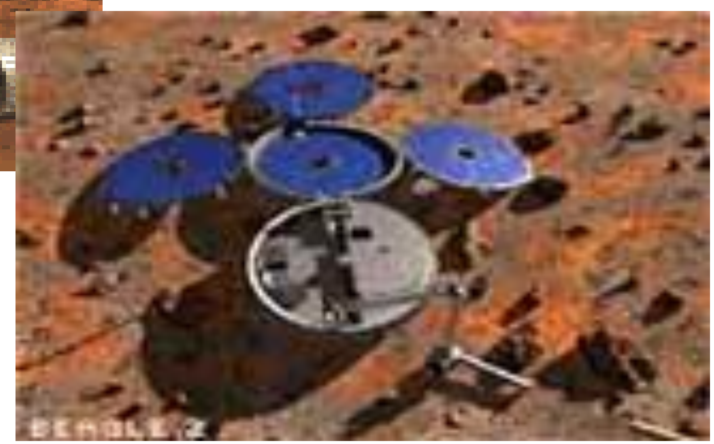


Phoenix

Sojourner



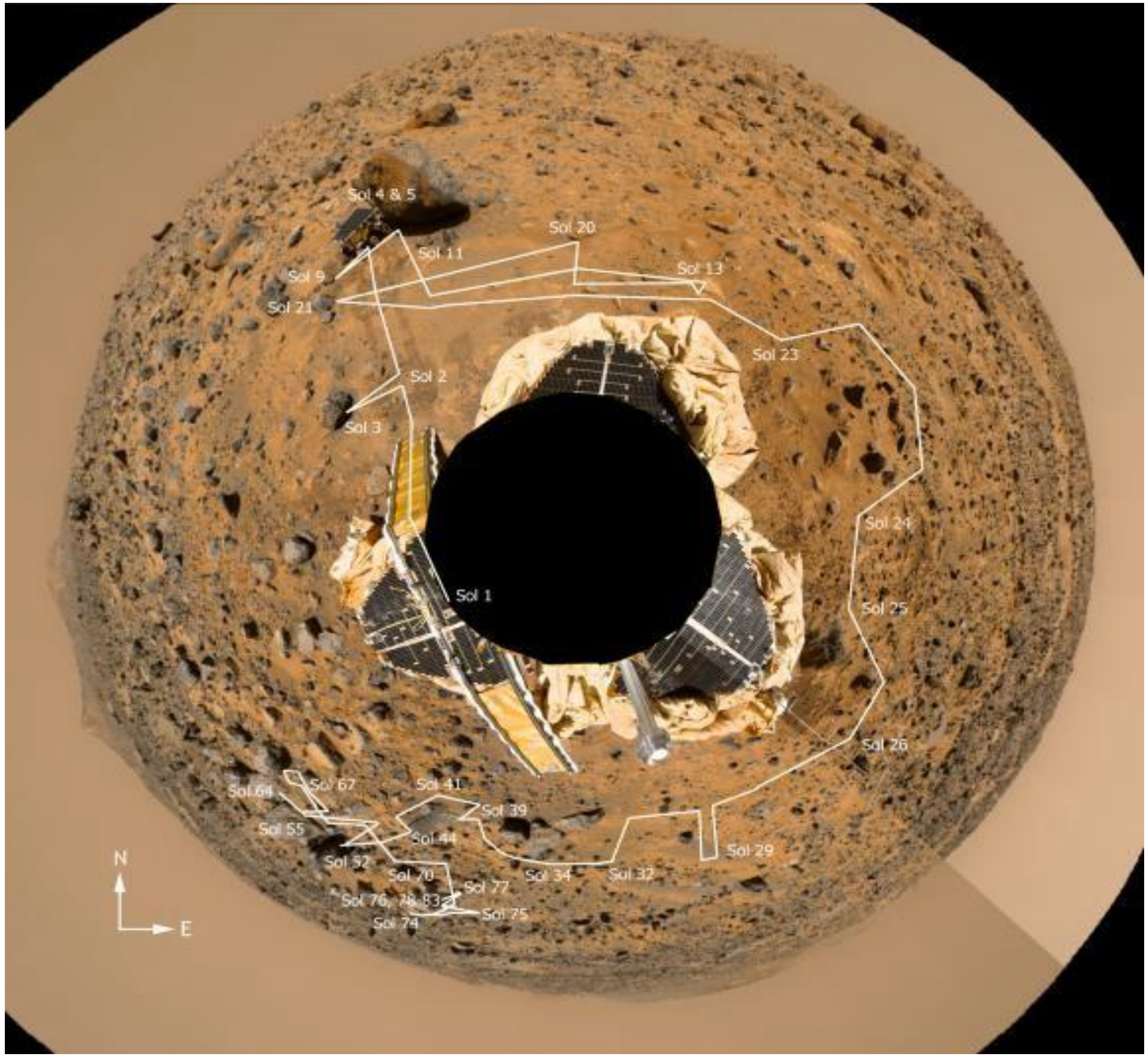
Spirit



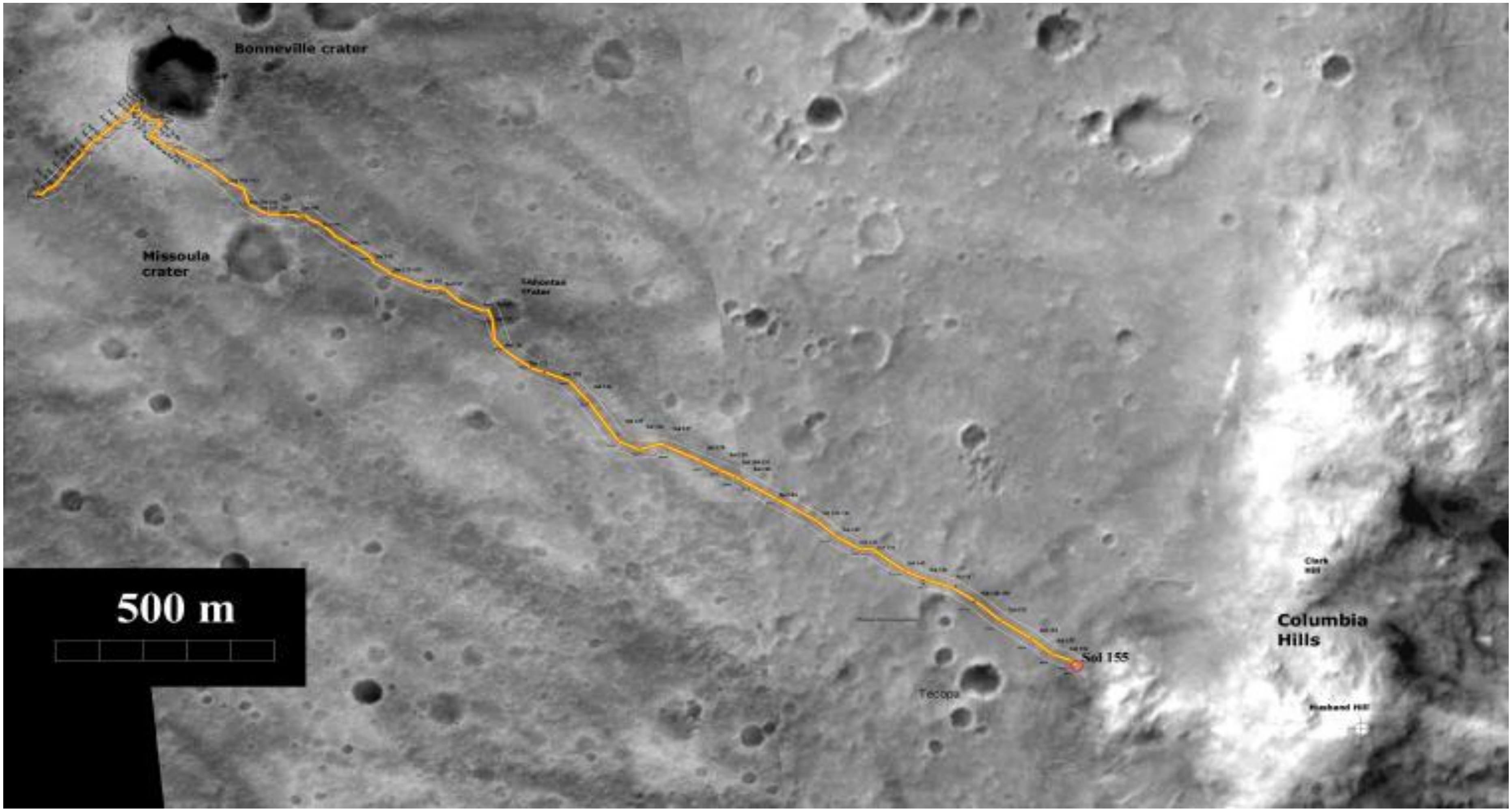
Beagle II

View from Sojourner

Missions - Pathfinder 1997

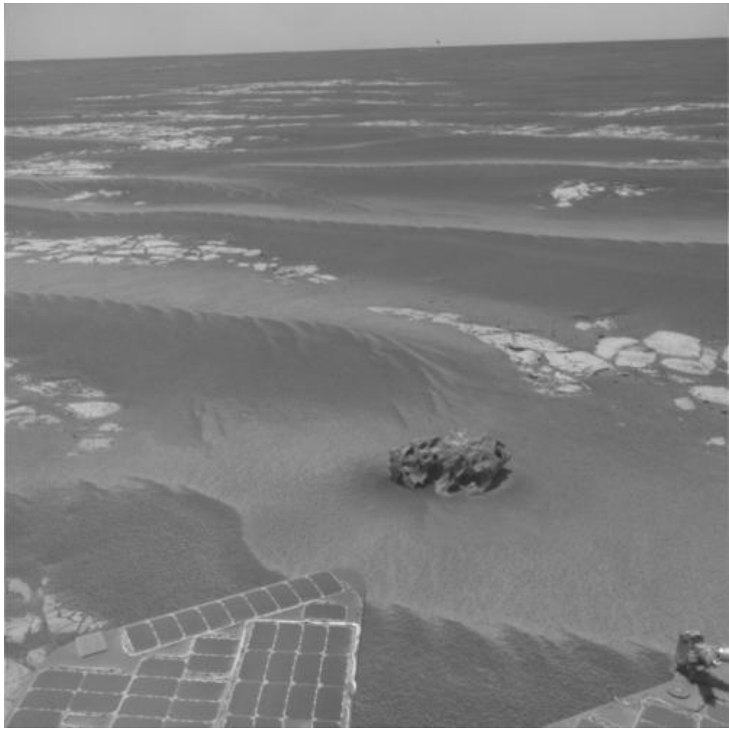


Missions – Spirit: Day 155

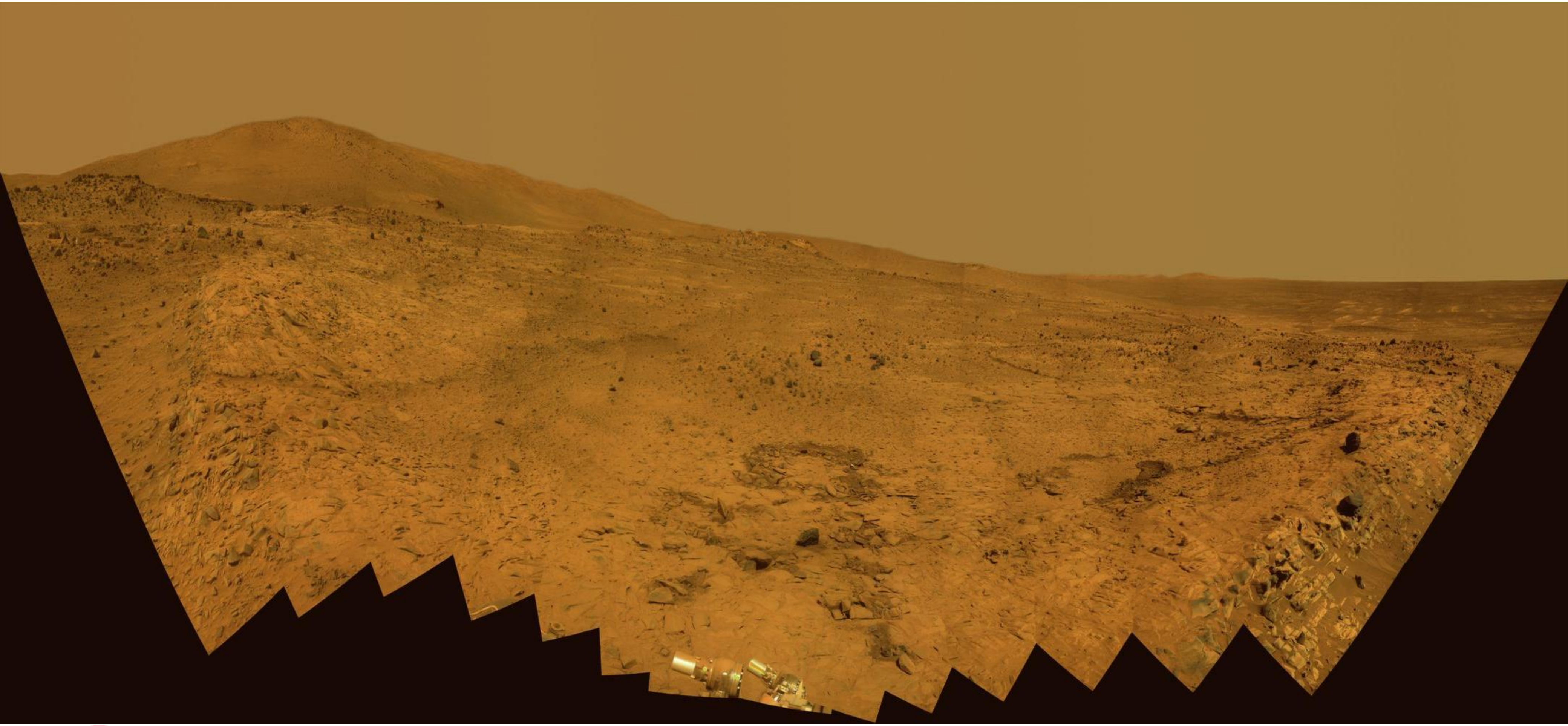


More Current Data

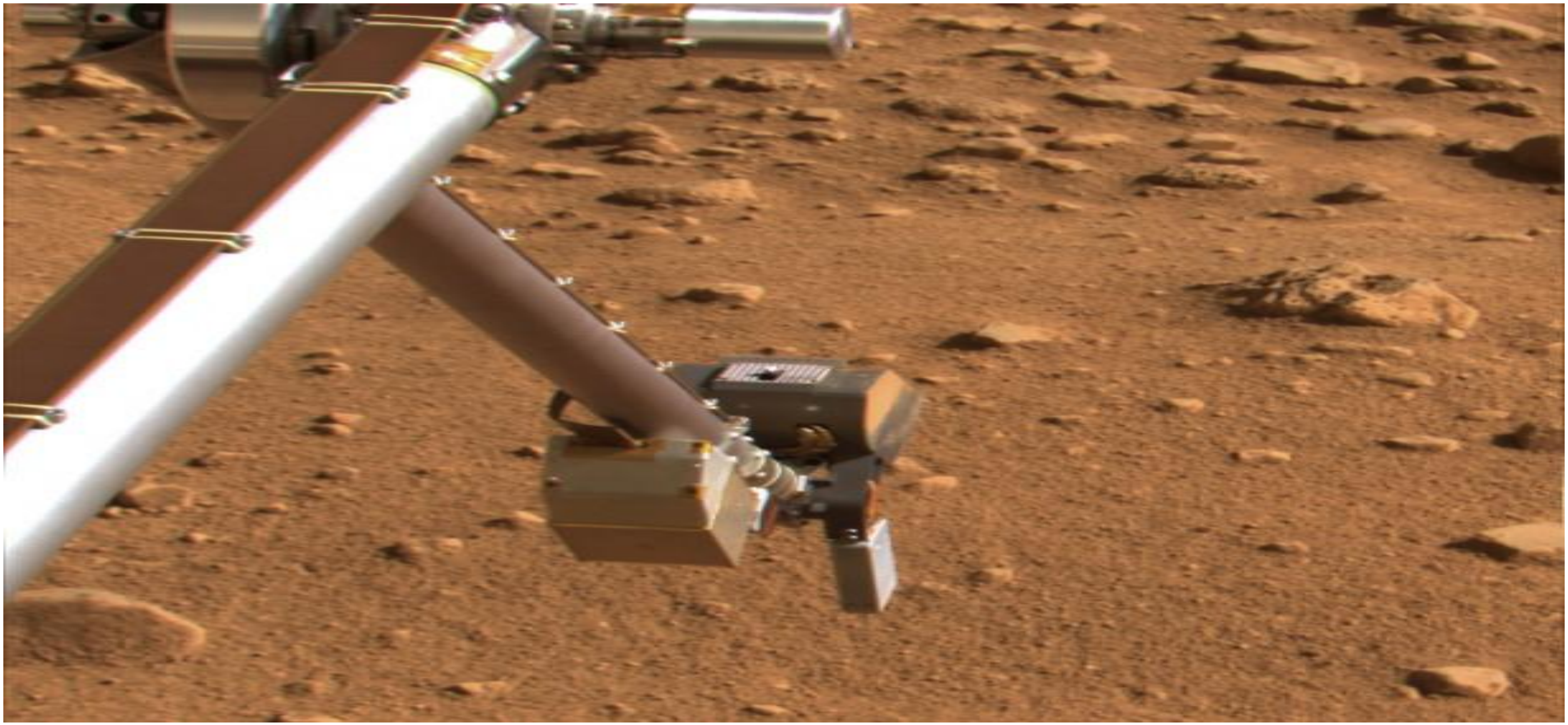
- As of Sol 2055 (Oct. 14, 2009), Spirit's total odometry remains at 7,729.93 meters (4.80 miles).
- As of Sol 2049 (Oct. 29, 2009), Opportunity's total odometry is 18,622.44 meters (11.57 miles).
- 2,022nd sol, (Oct. 1, 2009) Opportunity found another meteorite.
- Spirit is trapped in a sand pit.



A Panorama from Spirit



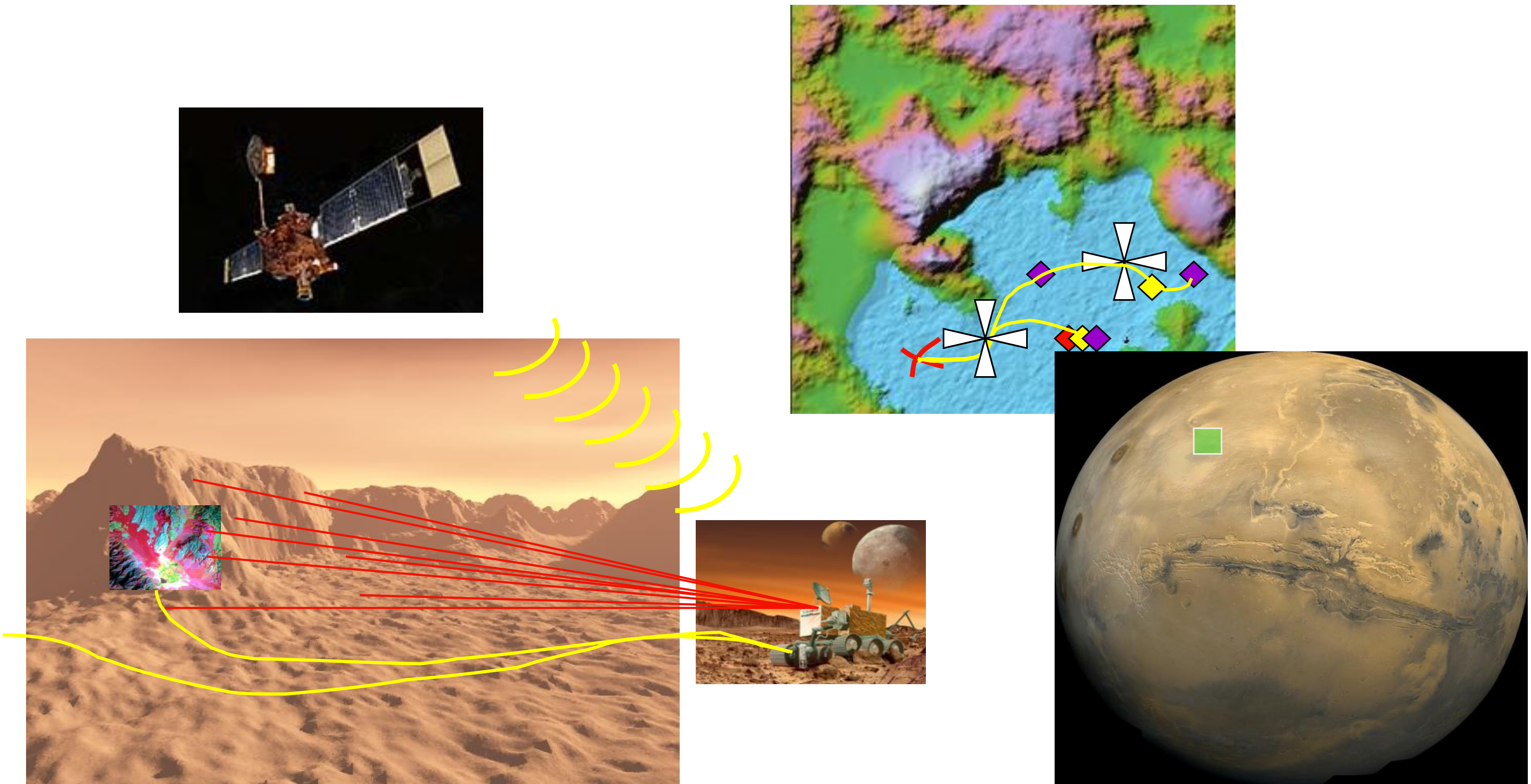
Phoenix in action



For more information visit:

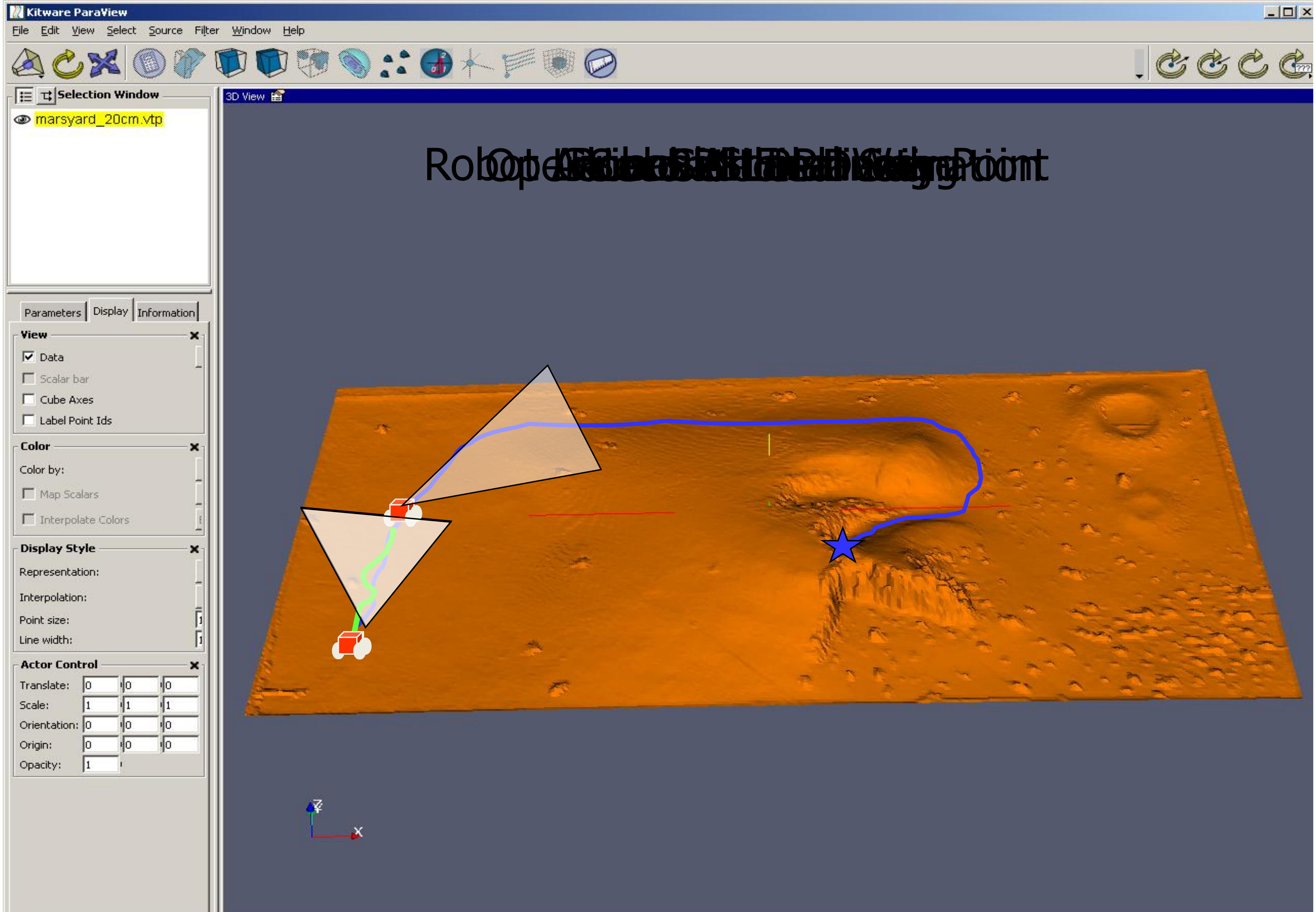
- http://mars.jpl.nasa.gov/MPF/
- http://marsrovers.jpl.nasa.gov/home/
- http://phoenix.lpl.arizona.edu/index.php
- http://www.google.com/mars/

Long-Term Goal: Autonomous Robotic Exploration



Current Research Objectives

- Over-the-horizon Navigation in a Single Command Cycle
- Assumptions:
  - Rough A Priori Knowledge:
    - Localization
    - Terrain
  - Terrain Sensing Using LIDAR



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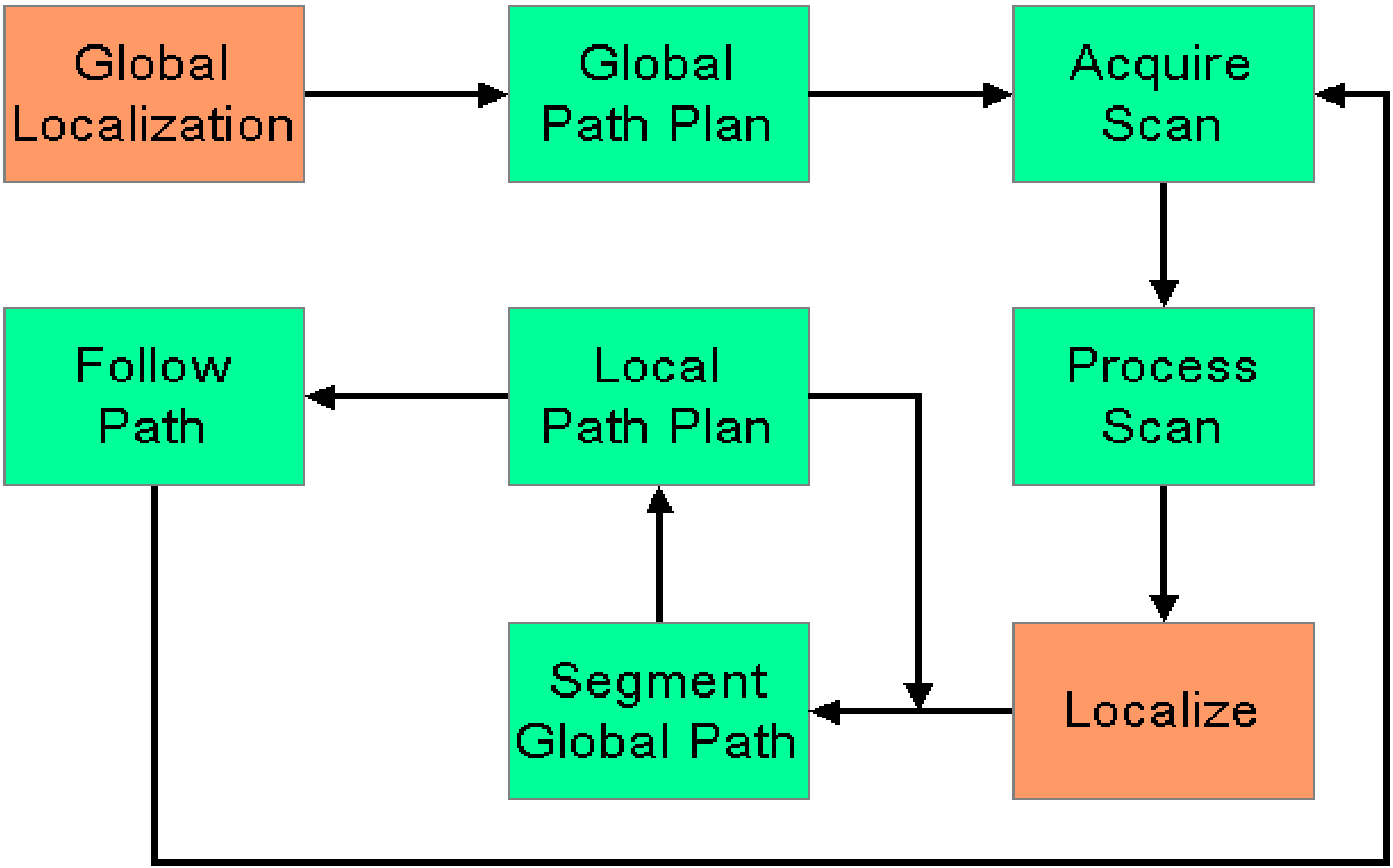
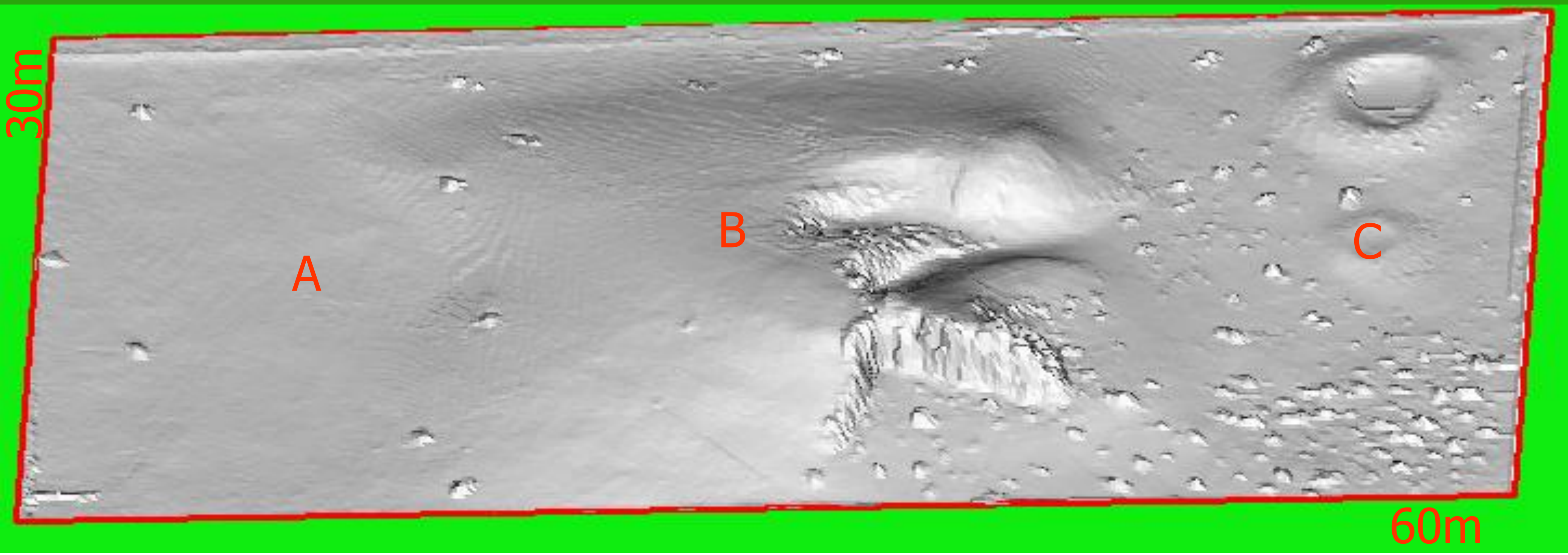
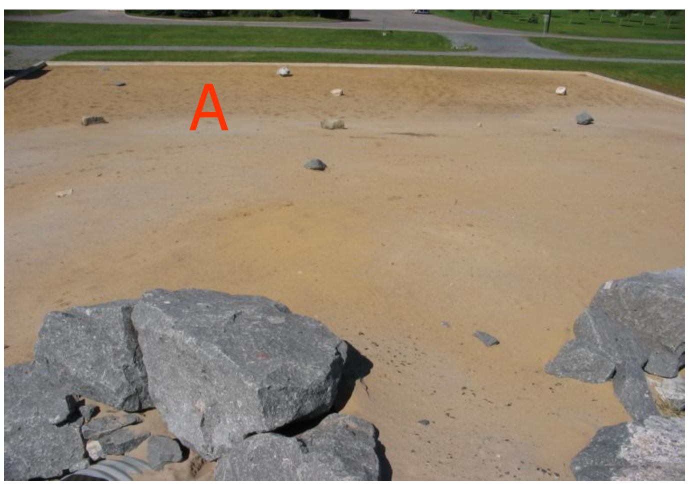

Global Localization
Global Path Plan
Acquire Scan
Follow Path
Local Path Plan
Process Scan
Segment Global Path
Localize

Experimental Testbed 2006

- CSA Mars Terrain
  - 60m x 30m
- Pioneer P2-AT Robot
- ILRIS-3D LIDAR
  - 3D point cloud
  - 1.5km-range (trimmed down to ~30m)
  - 40 degree FOV

Mars Emulation Terrain

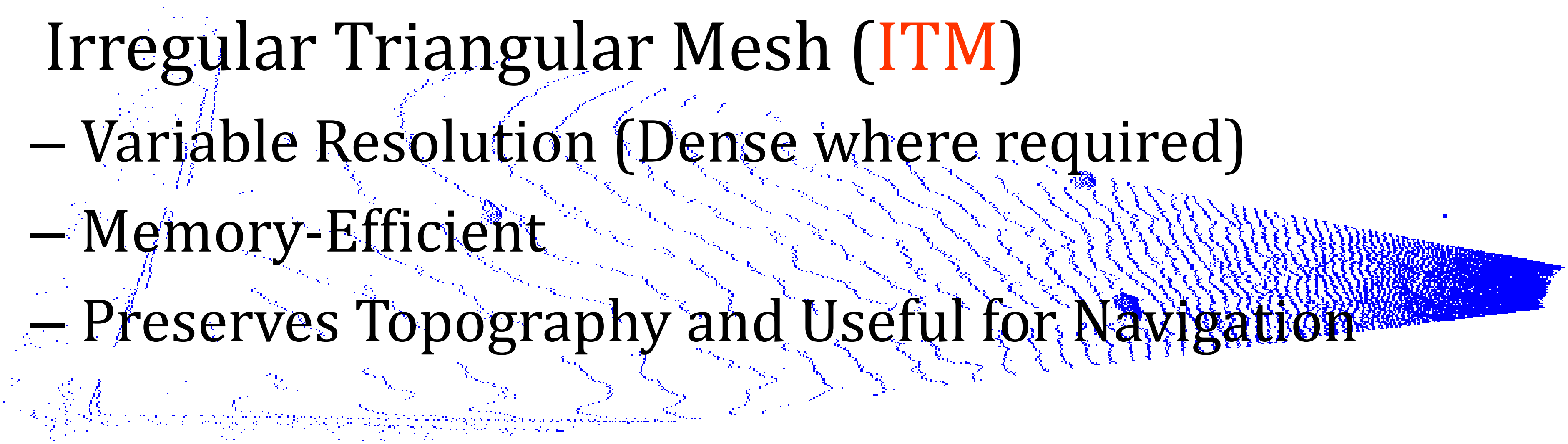




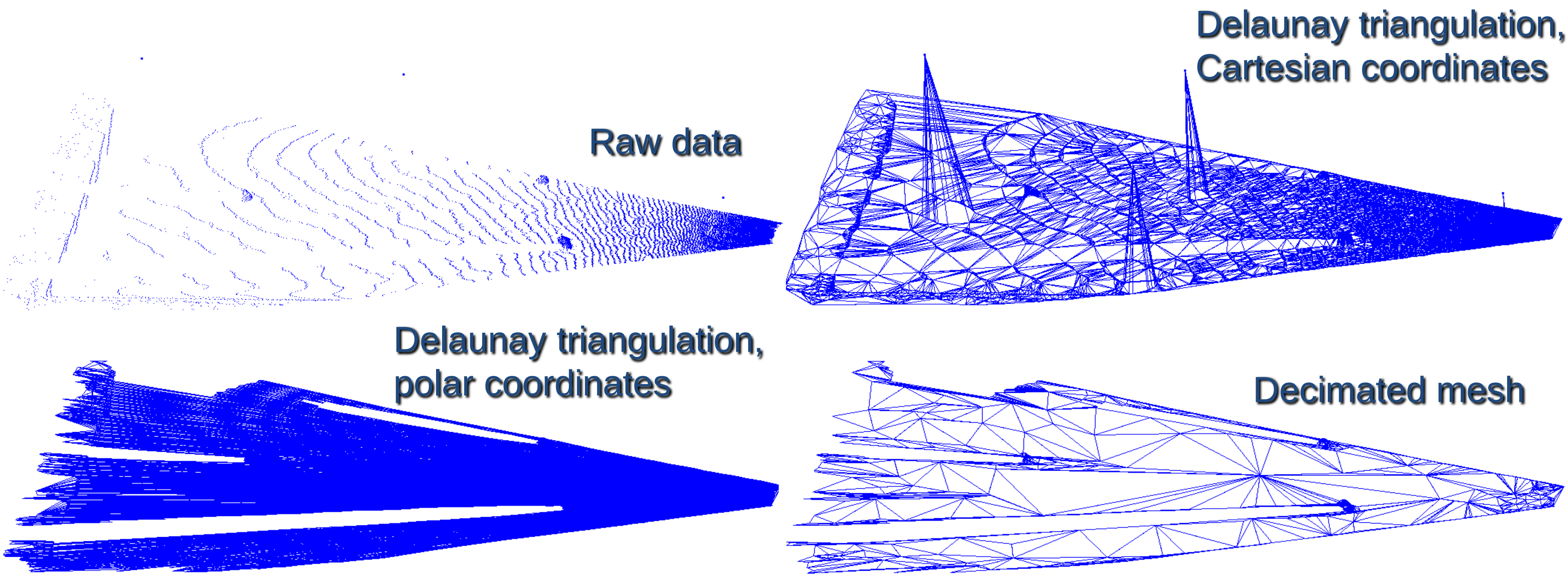
Terrain Modeling

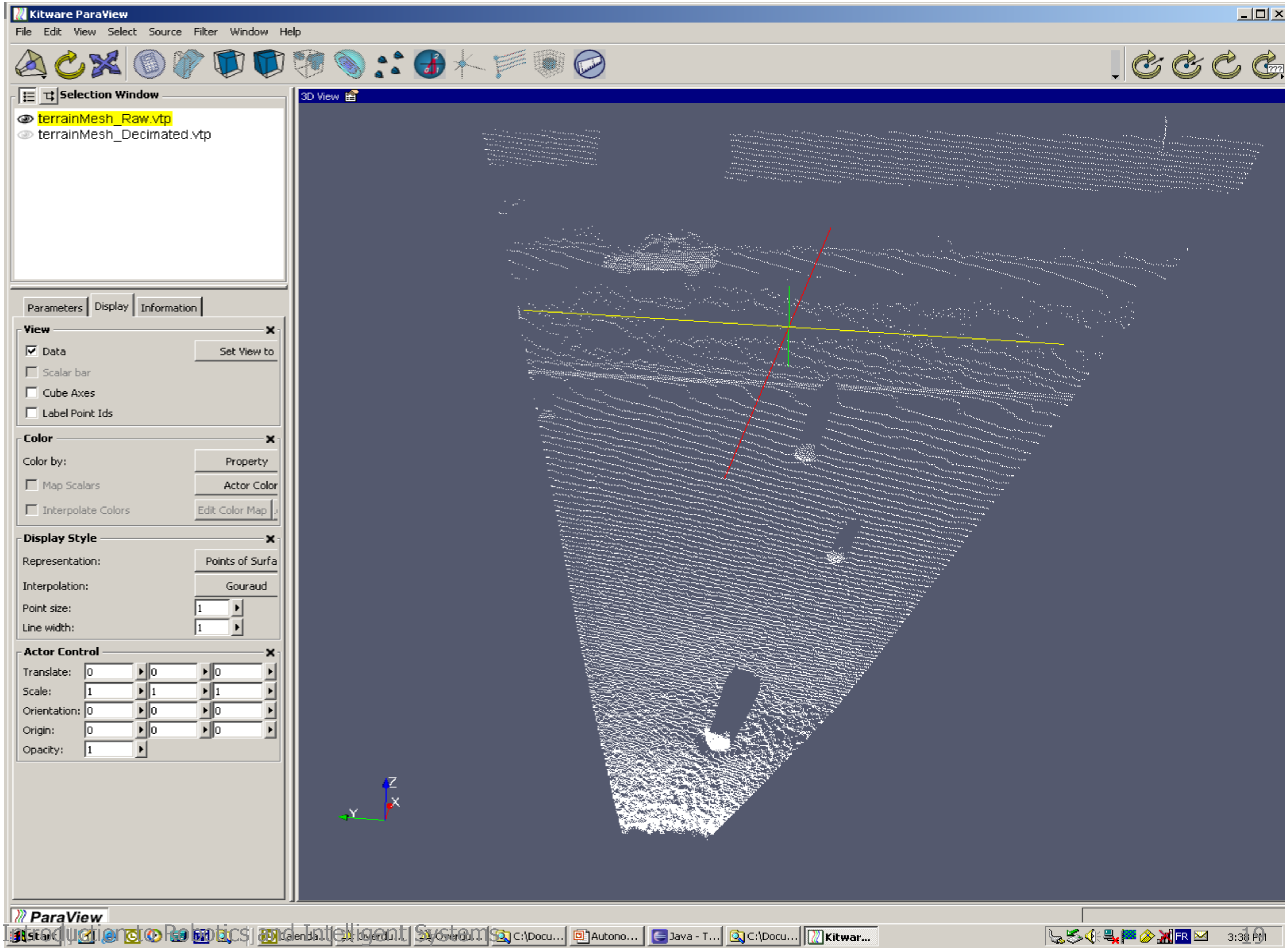
- Raw Data: 3D Point Cloud
  - Variable resolution
  - Long shadows
- Terrain Model based on

  Irregular Triangular Mesh (ITM)
  - Variable Resolution (Dense where required)
  - Memory-Efficient
  - Preserves Topography and Useful for Navigation



Terrain Modeling: Irregular Triangular Mesh (ITM)

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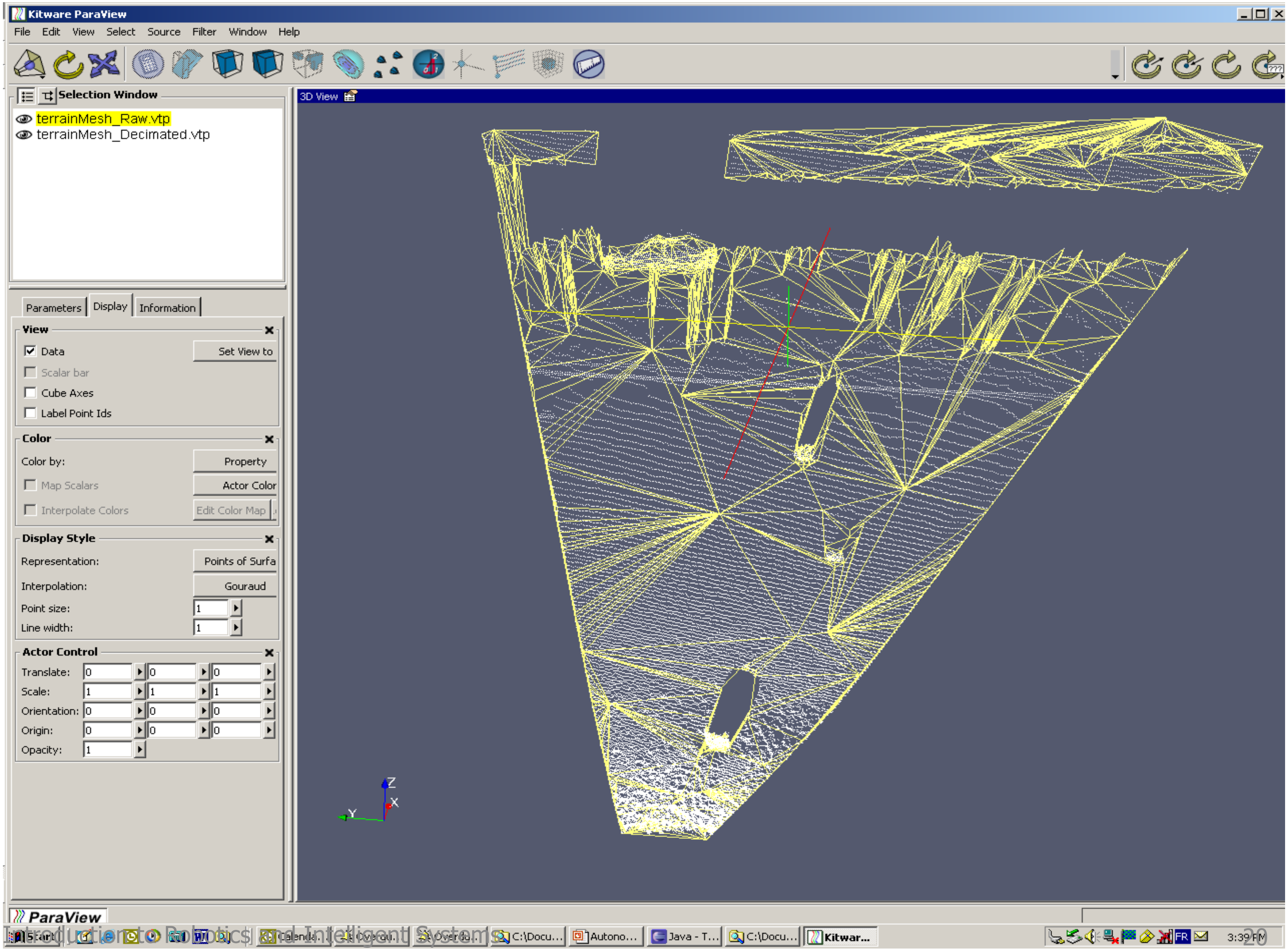

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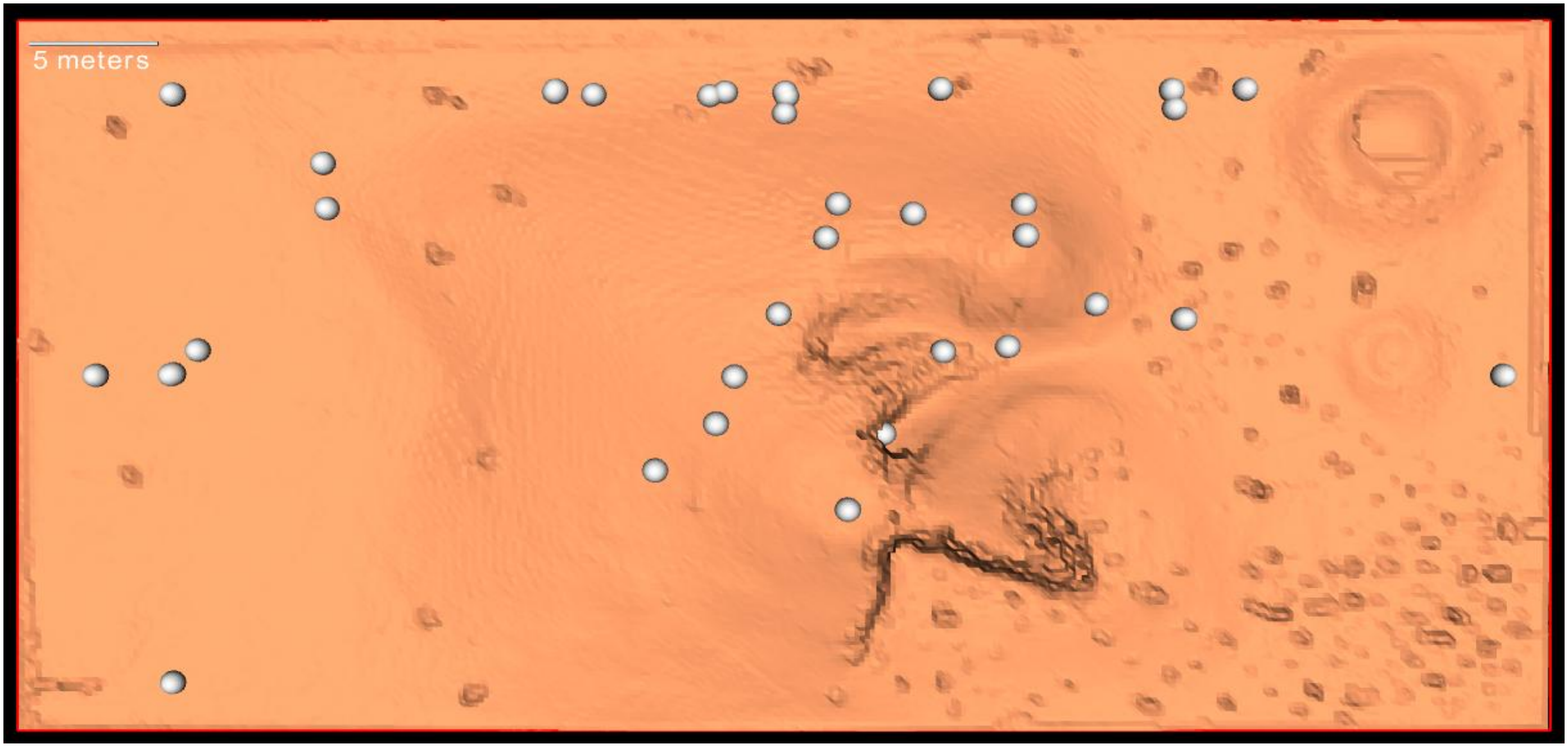
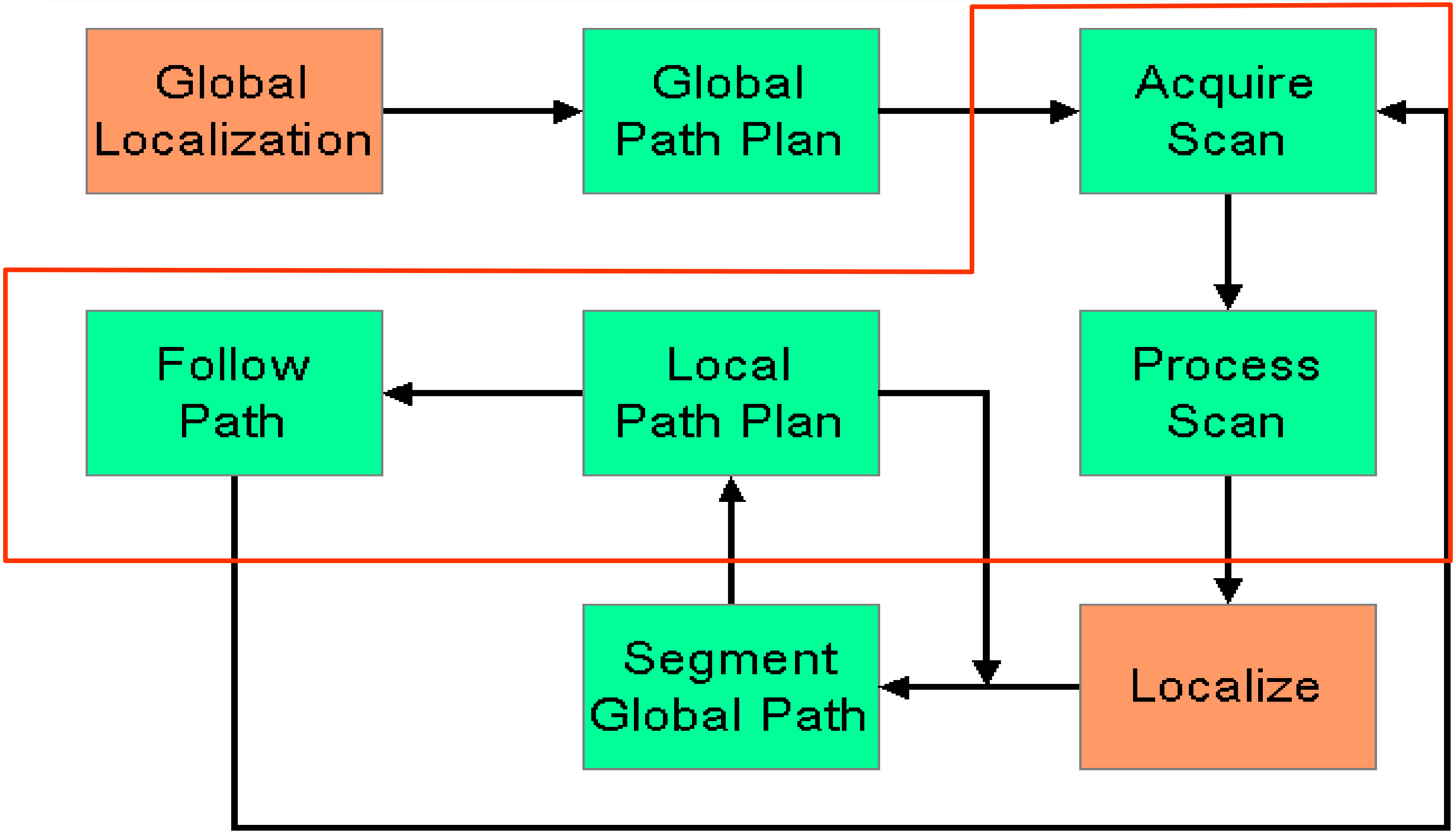
2006, Scans Collected: 96



2006, Over-the-Horizon Navigation

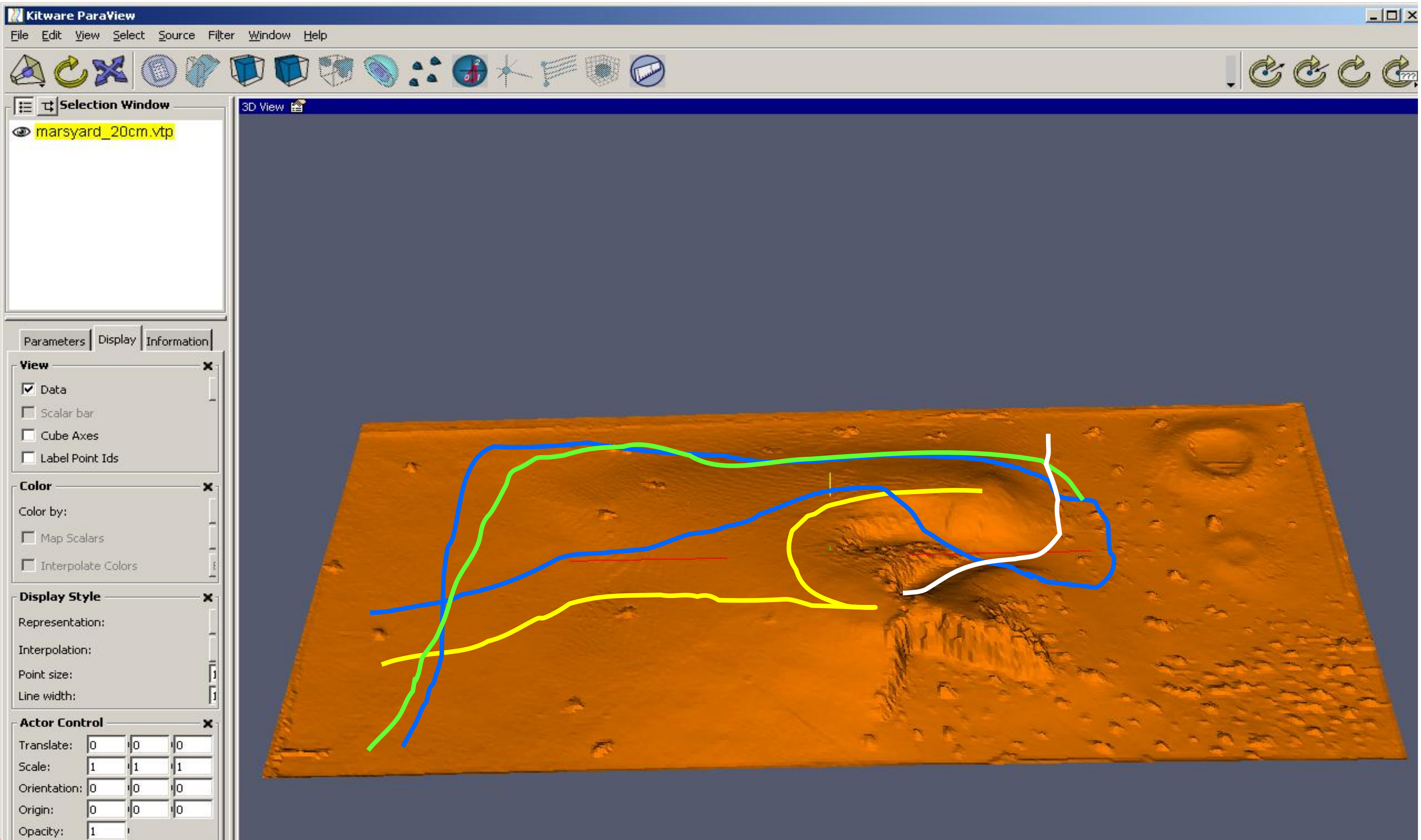


2006, Over-the-Horizon Traverses
Semi-Autonomous

- Successful Traverses
- A Sequence of Local Traverses
- Operator Intervention Necessary at Every Step (Semi-Autonomous)

- Achieved Traverse on the order of 150m

2006, Over-The-Horizon Traverses



Lessons Learned from 2006 Testing Period

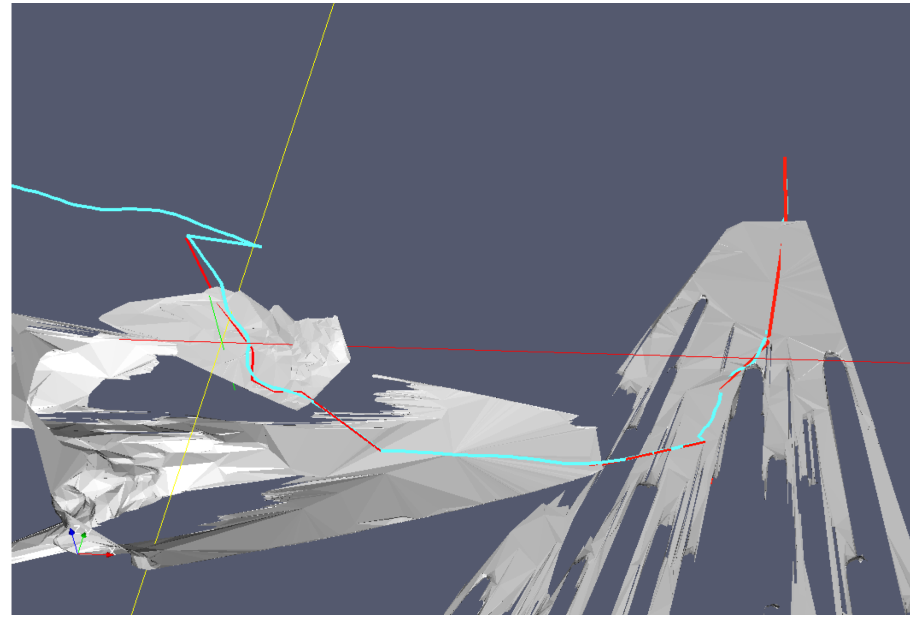
- Extensive Field Testing **EXTREMELY** useful!
- Validate Navigation Software
- Active Vision Great under Poor Lighting
- **Identify Issues Requiring further Development**

Lessons Learned

- Top level issues:
  - Environment Sensor Unwieldy
    - FOV Too Narrow
    - Logistics a Nightmare

Lessons Learned

- Top level issues:
  - Environment Sensor Unwieldy
    - FOV Too Narrow
    - Logistics a Nightmare
  - Horizon Sometimes Much Closer than Expected
  - Environment Scans Need to be Interpreted (Shadows)

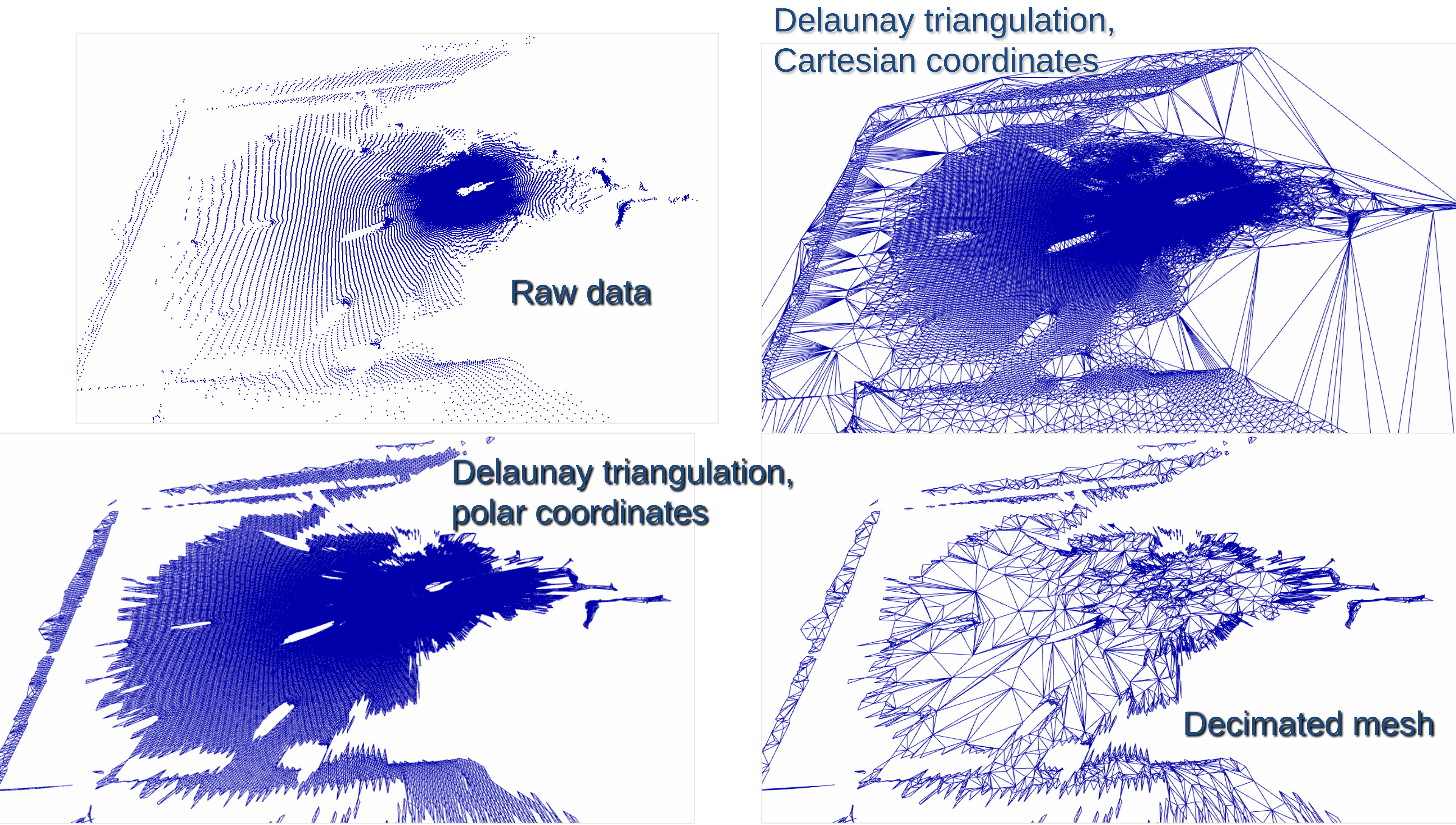


2007 Test Campaign

Updates in the Testbed 2007

A 360^o LIDAR scanner
- A SICK LRF
- Mounted on a pan-unit

Scan Processing



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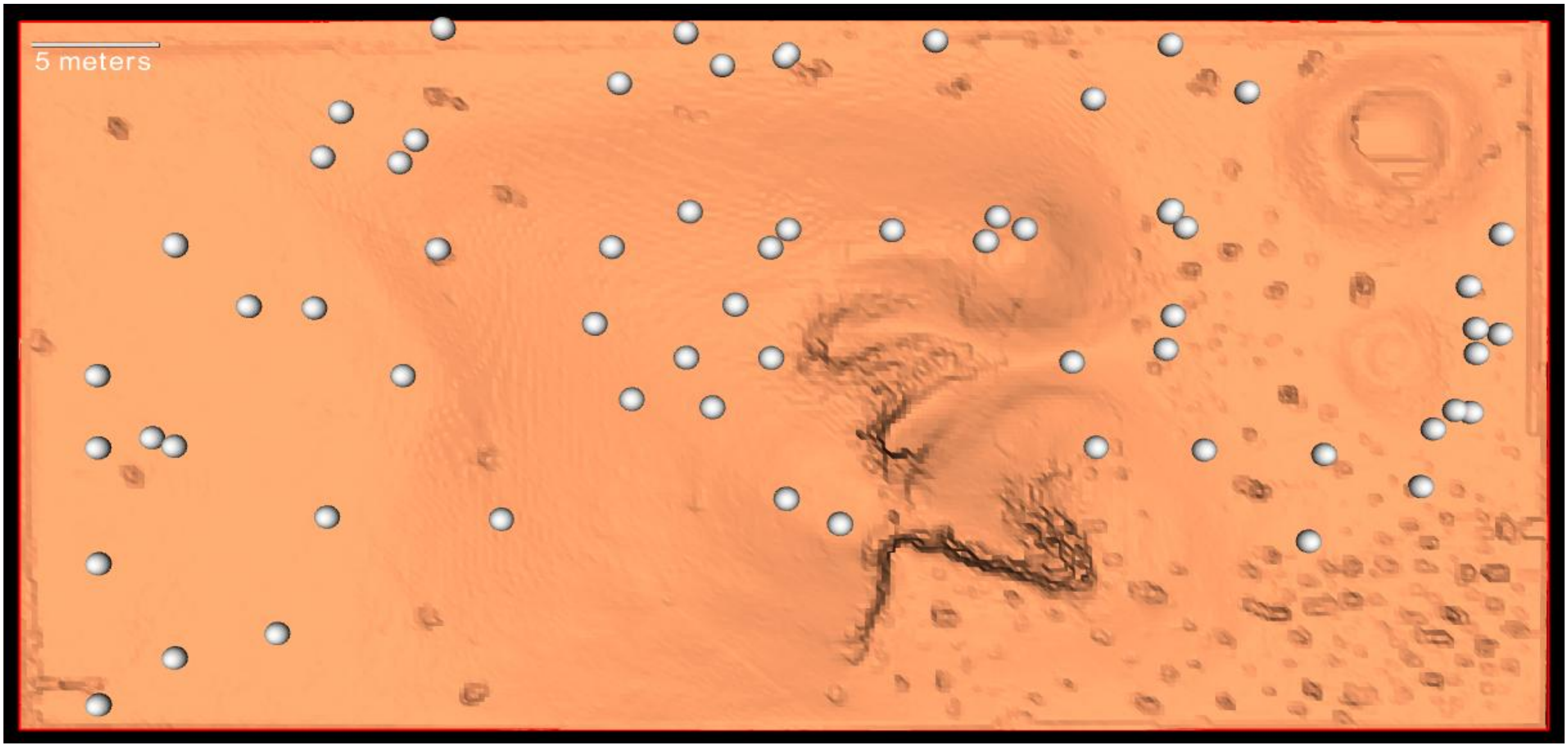


Comparison between the two LIDARs

SICK on Pan Unit

- 360^o coverage
- Portable
- Easy Interface
- Limited Range
- Lower resolution
- Lower accuracy
- **Low cost ~12K**

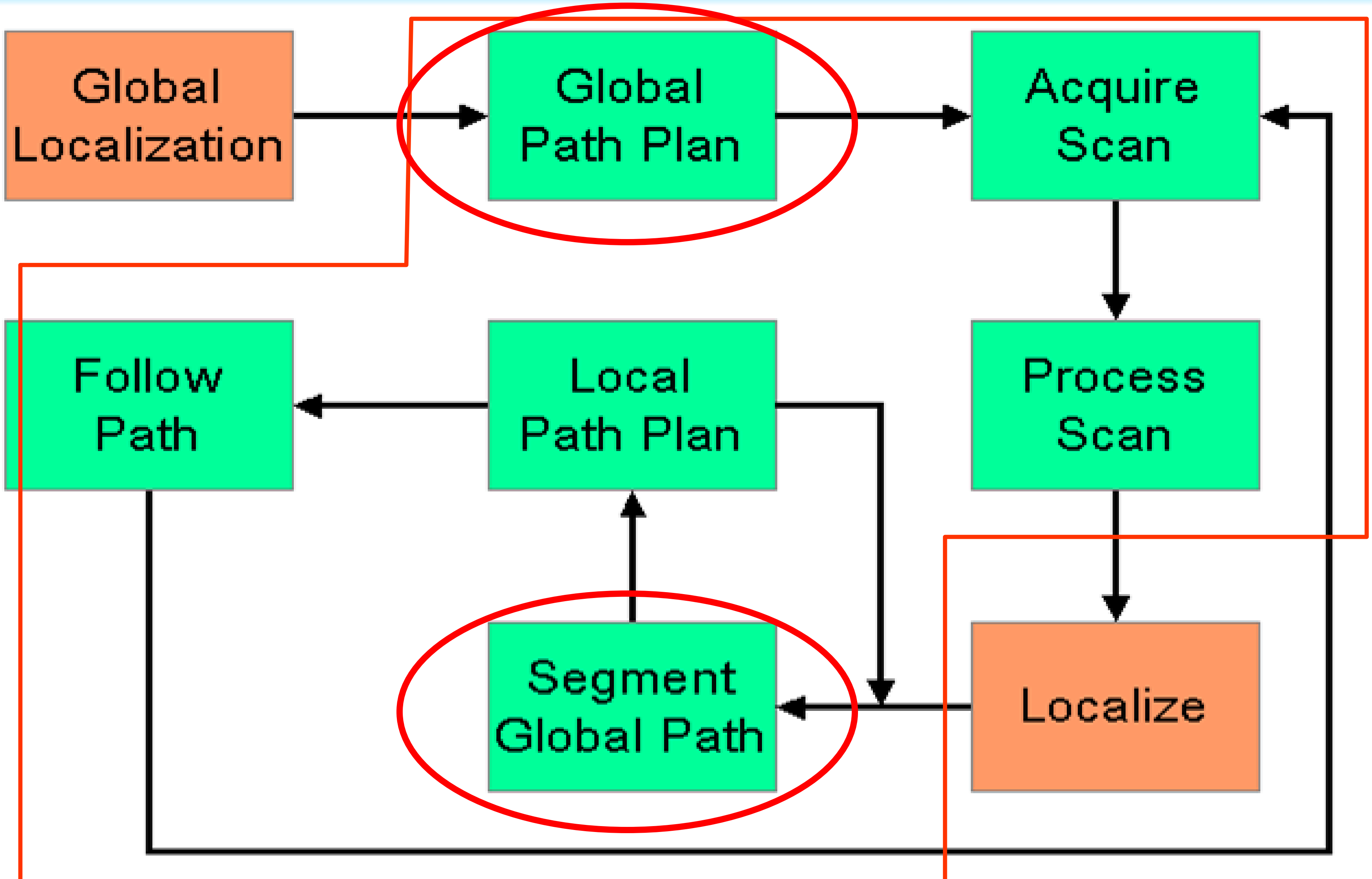
ILRIS 3D

- Highly accurate
- Long range
- High resolution
- Limited field of View
- Restrictive Interface
- Unwieldy
- Not Portable
- **High cost ~250K**

Irregular Triangular Mesh Decimation

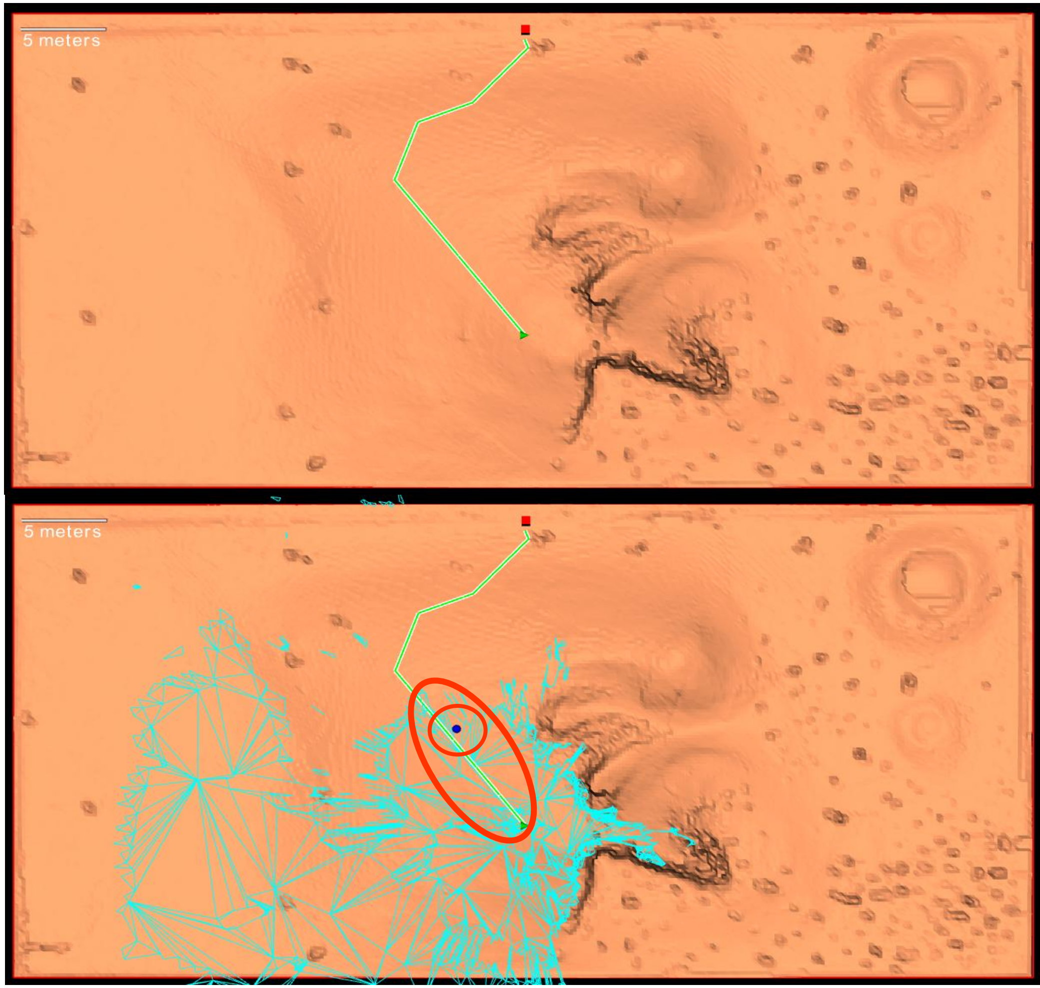
				Target Decimation Ratio				
				80%		90%		95%
2006	Points (mean)	31200	6530	79.00%	3440	88.86%	2090	93.09%
	Triangles (mean)	61700	12300	80.00%	6190	89.91%	3590	94.01%
2007	Points (mean)	111000	23400	78.91%	12500	88.72%	6700	93.69%
	Triangles (mean)	216000	43300	80.00%	21600	90.00%	10900	94.98%
								Acceptable error 1.5cm

2007, Over-the-Horizon Navigation



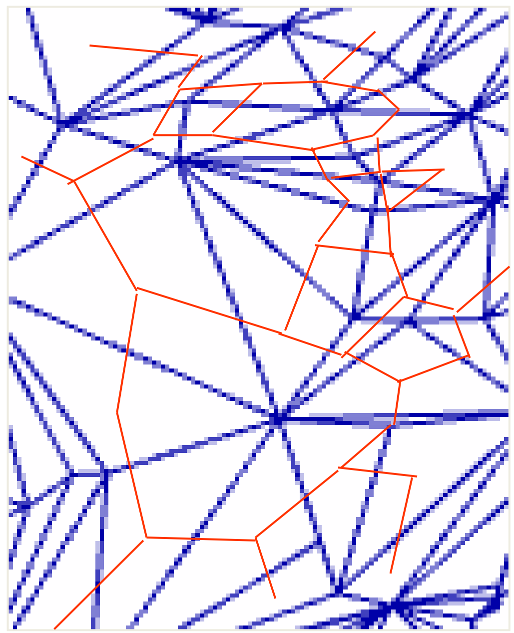
Global Path Plan and Segmentation

- Produce a rough global path using the low-resolution model
- Find the portion of the global path that is inside the local scan
- Select the largest acceptable triangle closest to the furthest accessible point



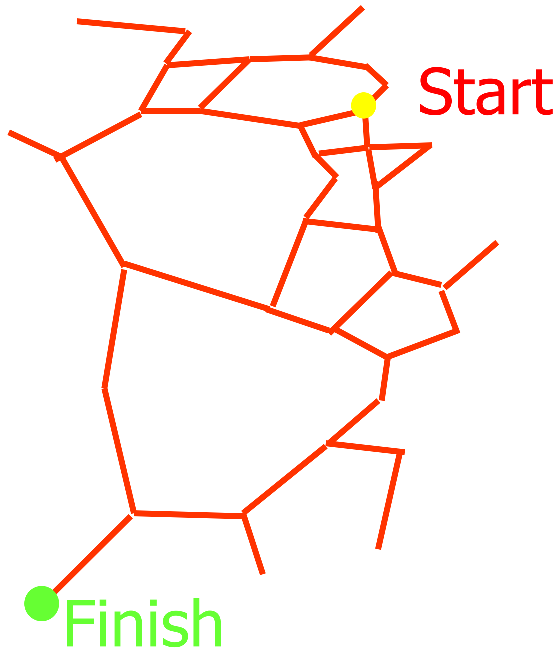
Path Planning

- Convert ITM into Connected Graph



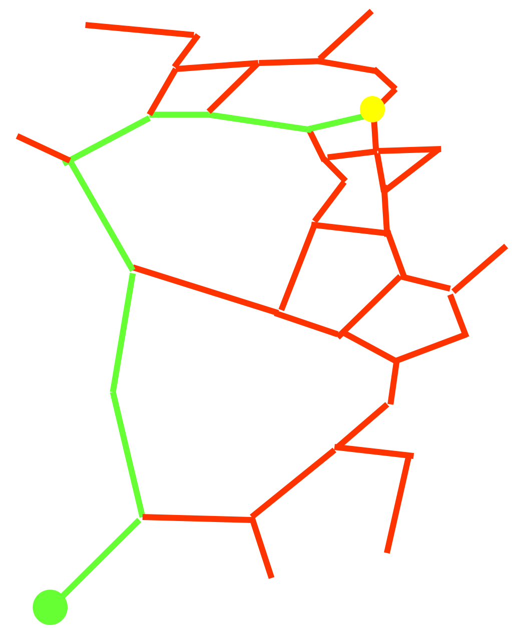
Path Planning

- Convert ITM into Connected Graph
- Path Planning using Graph Search Algorithms:
  - Dijkstra, A*



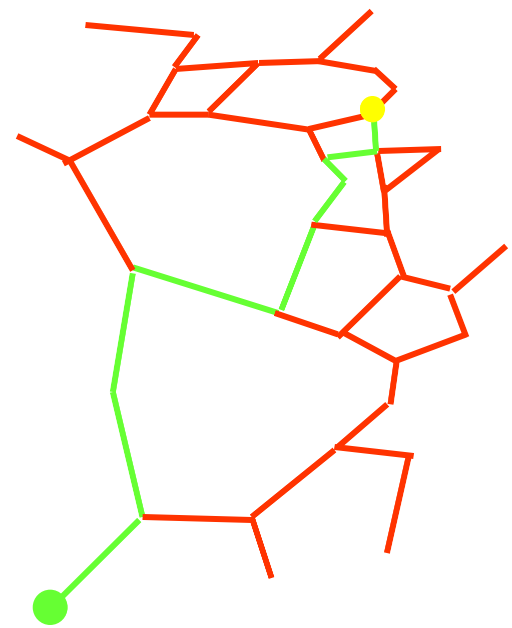
Planning

- Convert ITM into Connected Graph
- Path Planning using Graph Search Algorithms:
  - Dijkstra, A* search algorithms
- Different Cost Functions Q
  - Number of triangles $Q=1$



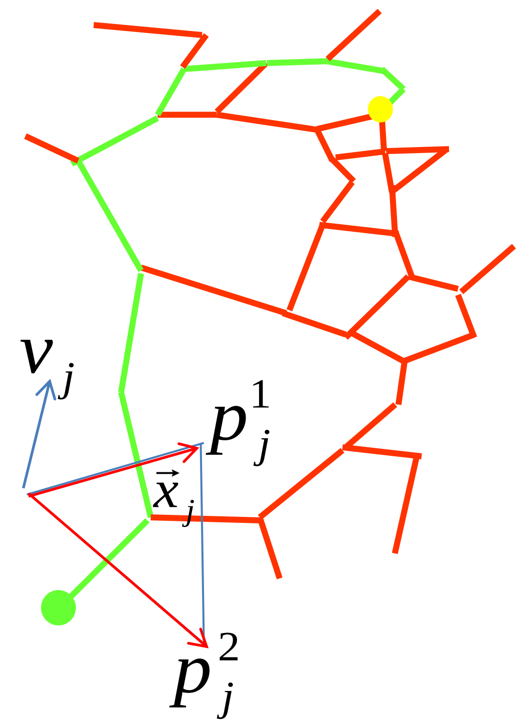
Planning

- Convert ITM into Connected Graph
- Path Planning using Graph Search Algorithms:
  - Dijkstra, A*
- Different Cost Functions Q
  - Number of triangles
  - Euclidian distance $Q = \left\| \vec{x}_i - \vec{x}_j \right\|$



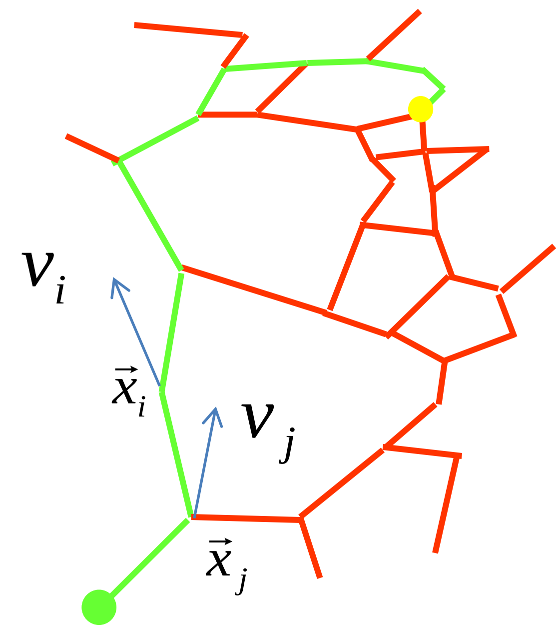
Planning

- Convert ITM into Connected Graph
- Path Planning using Graph Search Algorithms:
  - Dijkstra, A*
- Different Cost Functions Q
  - Number of triangles
  - Euclidian distance
  - Slope of each triangle $v_j = \dfrac{p_j^1 \times p_i^2}{\|p_j^1\|\|p_j^2\|}$



Planning

- Convert ITM into Connected Graph
- Path Planning using Graph Search Algorithms:
  - Dijkstra, A*
- Different Cost Functions Q
  - Number of triangles
  - Euclidian distance
  - Slope of each triangle
  - Cross triangle slope



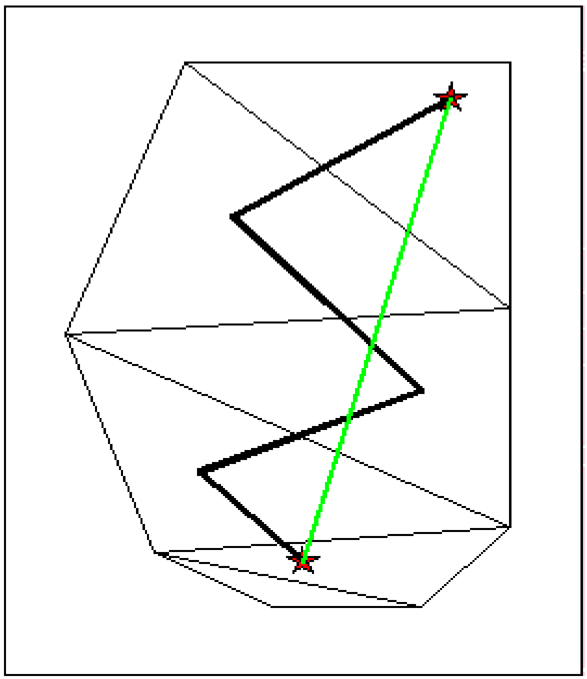
Path Planning

- Convert ITM into Connected Graph
- Path Planning using Graph Search Algorithms:
  - Dijkstra, A*
- Cost function:
  - Distance travelled
  - Penalty for uphill slope
  - Infinite cost for moving into too-steep triangles
  - Roughness of the area under the footprint of the robot
  - A* is biasing the cost towards the destination

Path Simplification

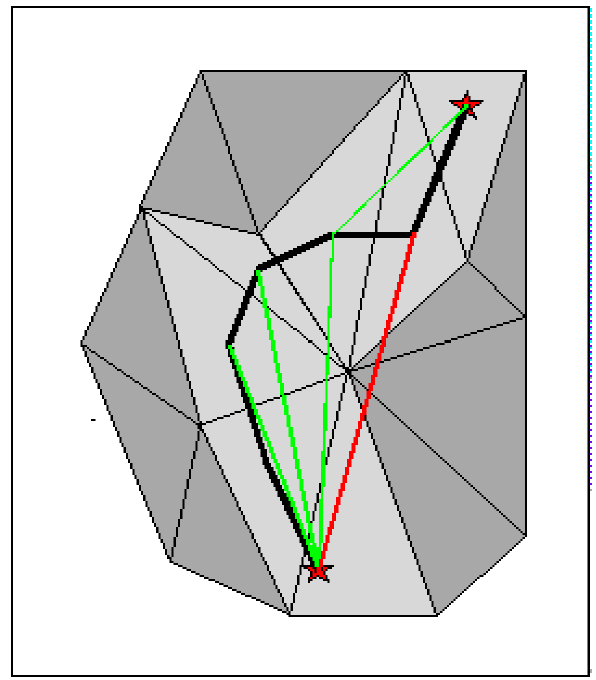
- Path Simplification

  Point-Robot

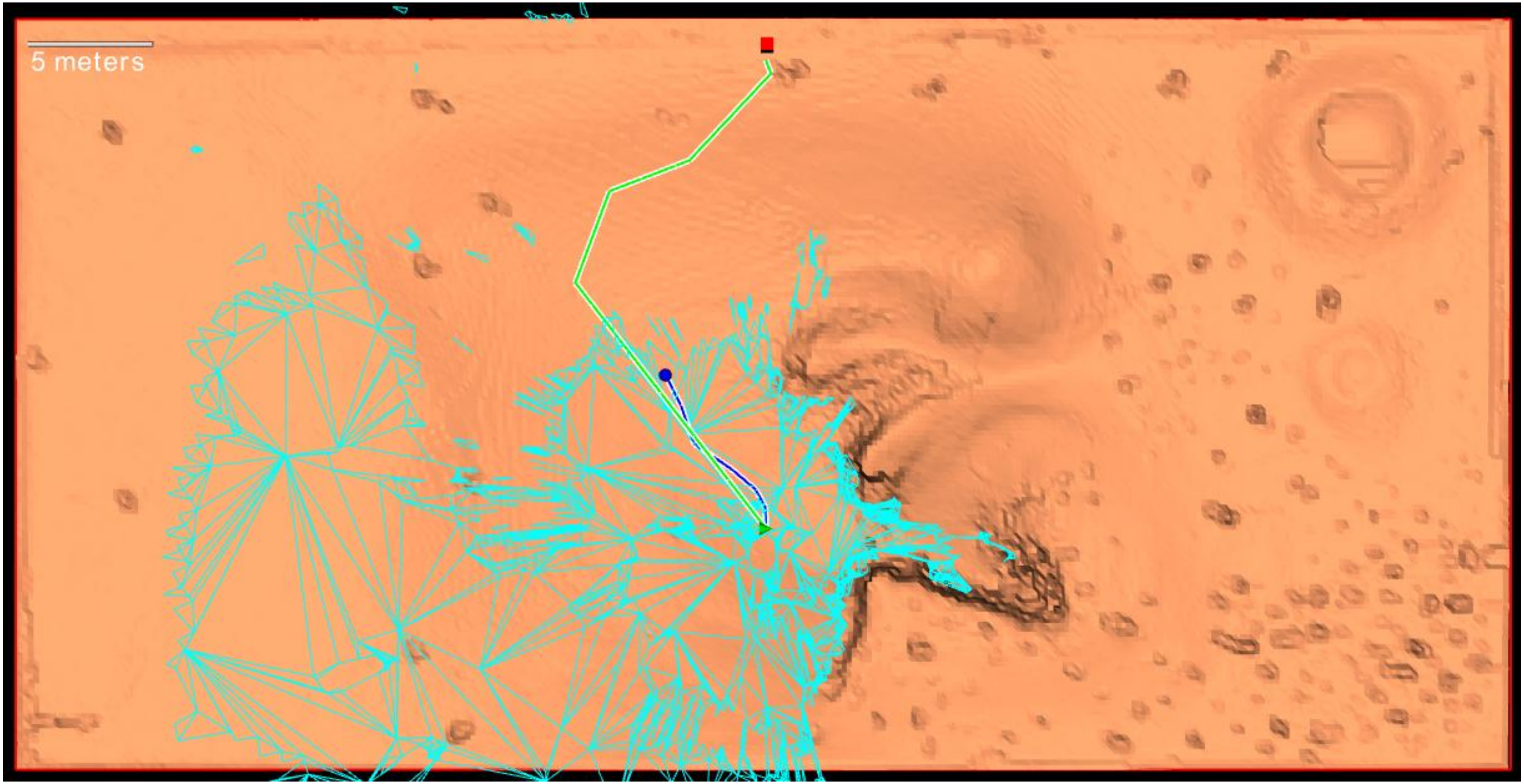


- Path Simplification

  Safety Corridor



Local Path Plan



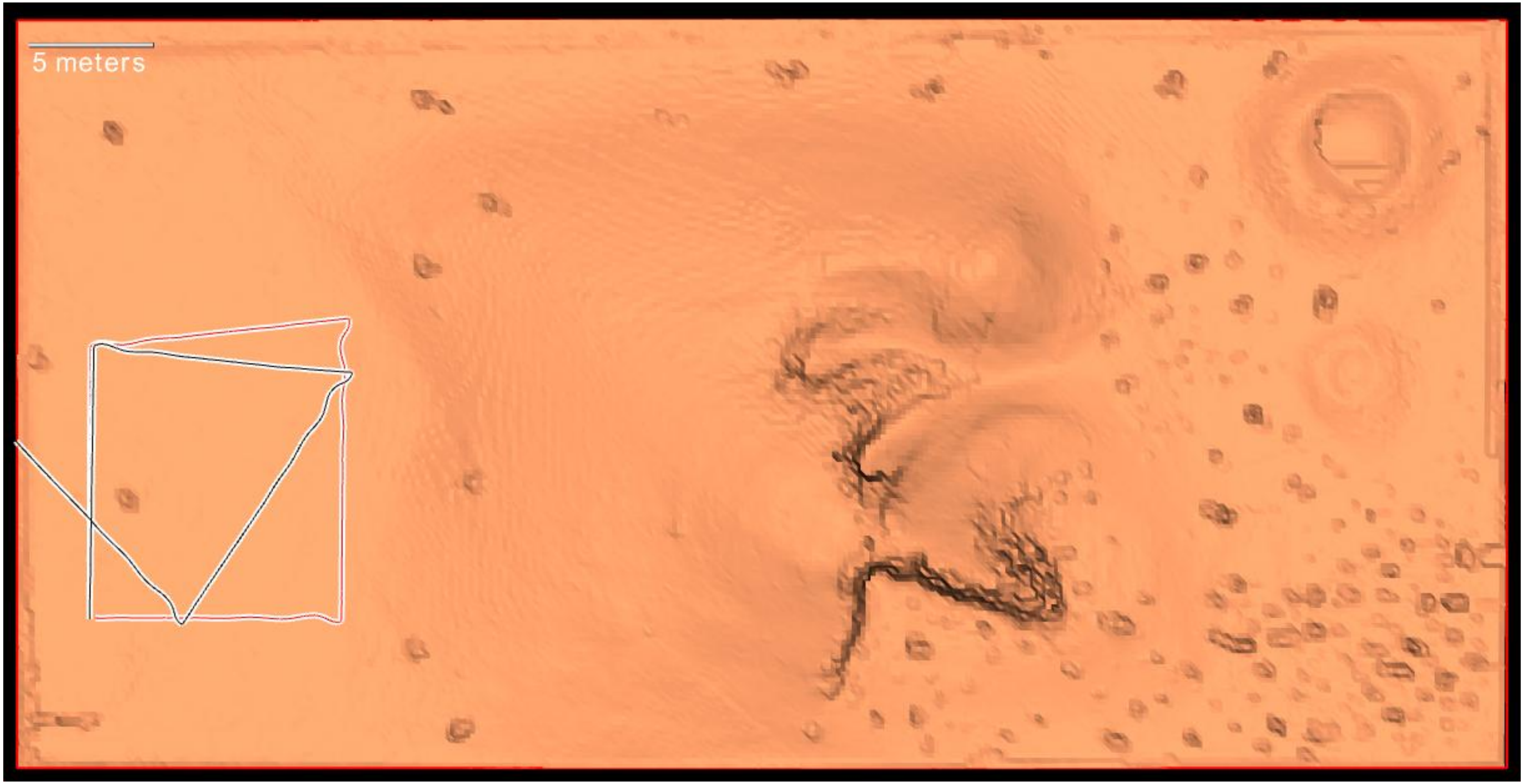
Motion Control

- Sensor Suite: Wheel Odometry, IMU, Heading sensor, No Visual Odometry
- 3D Pose Estimation:

  Filter combines IMU+Odometry

  No uncertainty estimation (currently)
- Path approximated with Catmull-Rom spline for smoothness
- Astolfi controller follows the spline trajectory

Closed Loop Tests



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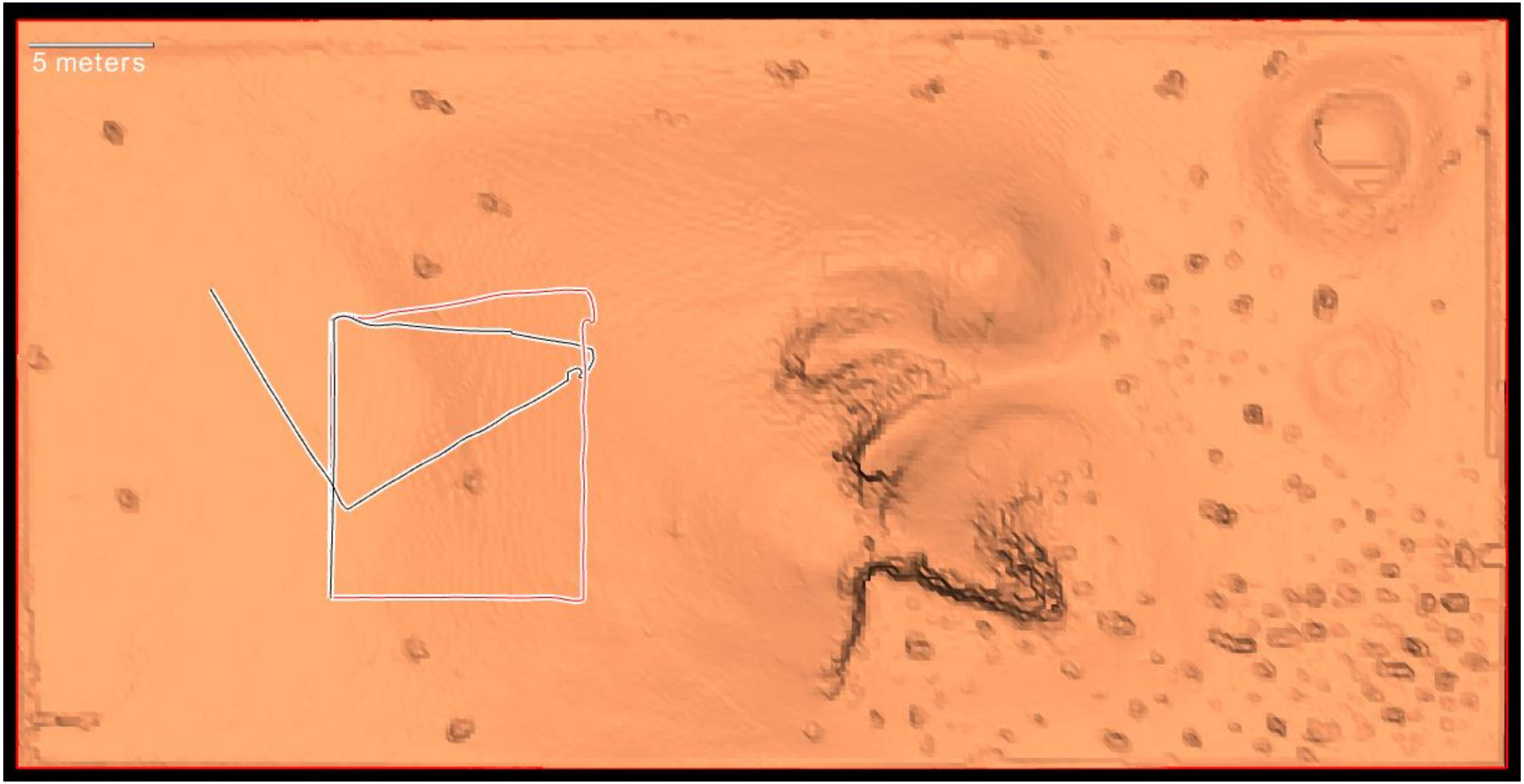

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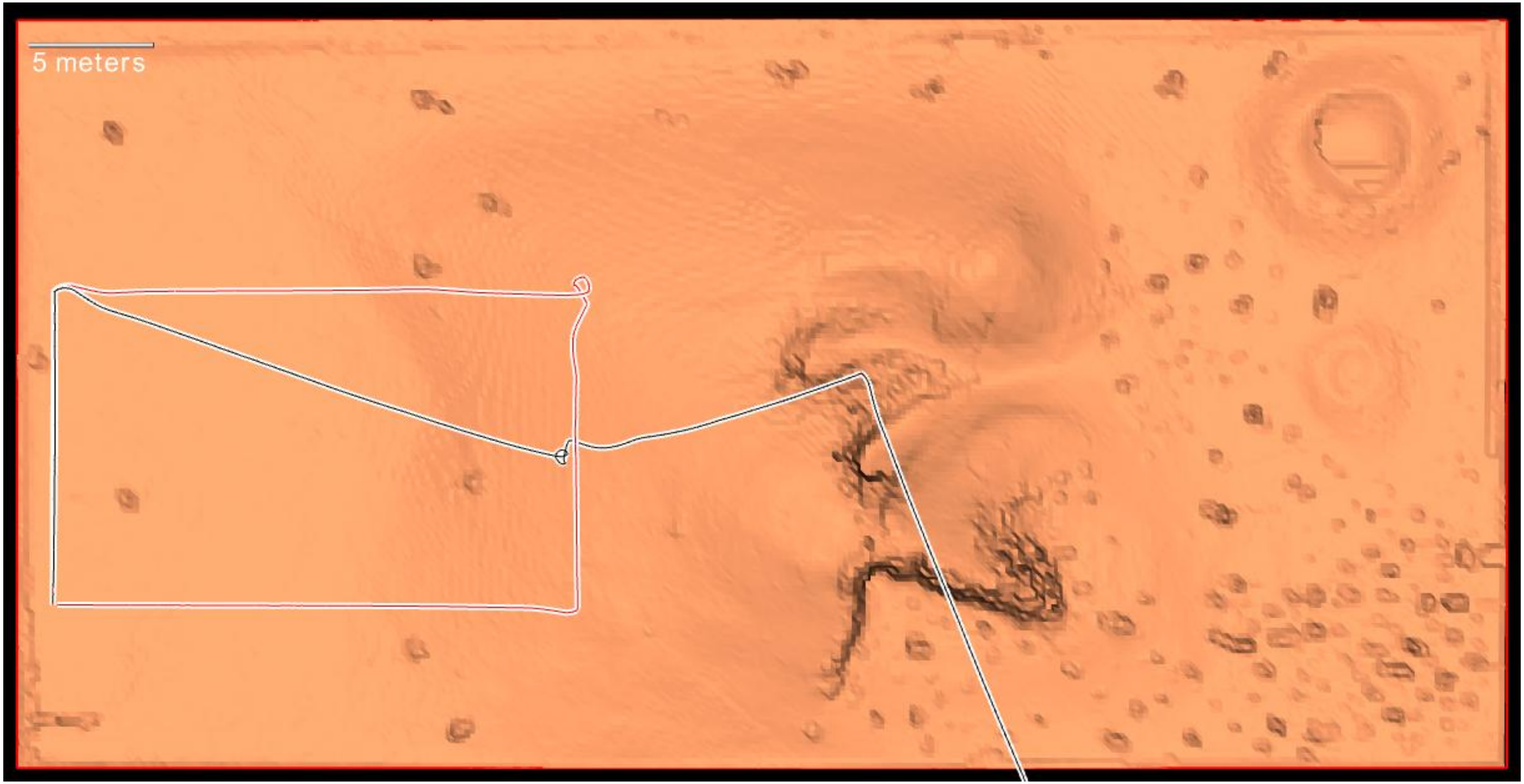
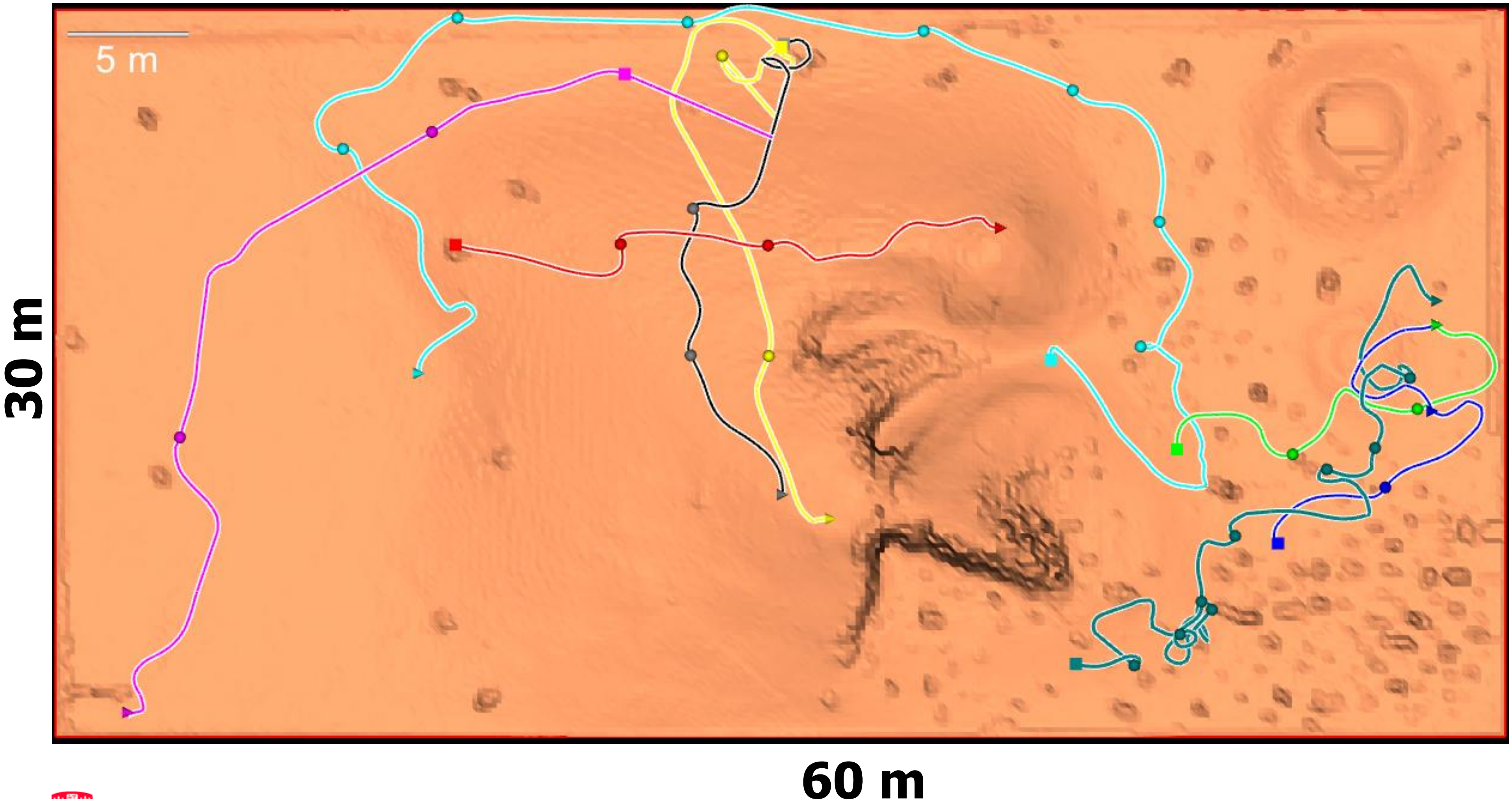
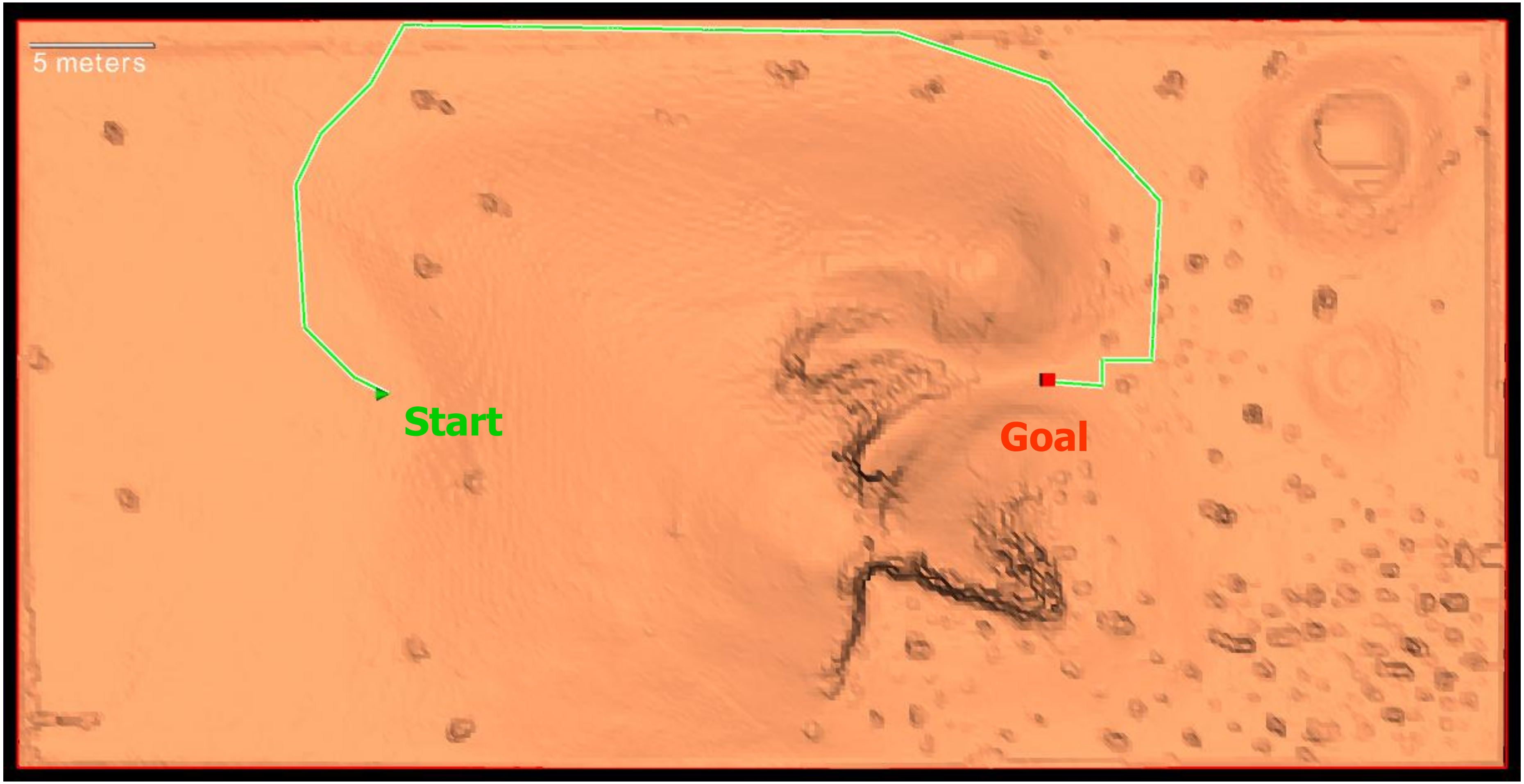


The Mars Terrain and Trajectories



Fully Autonomous Navigation
from flat to canyon



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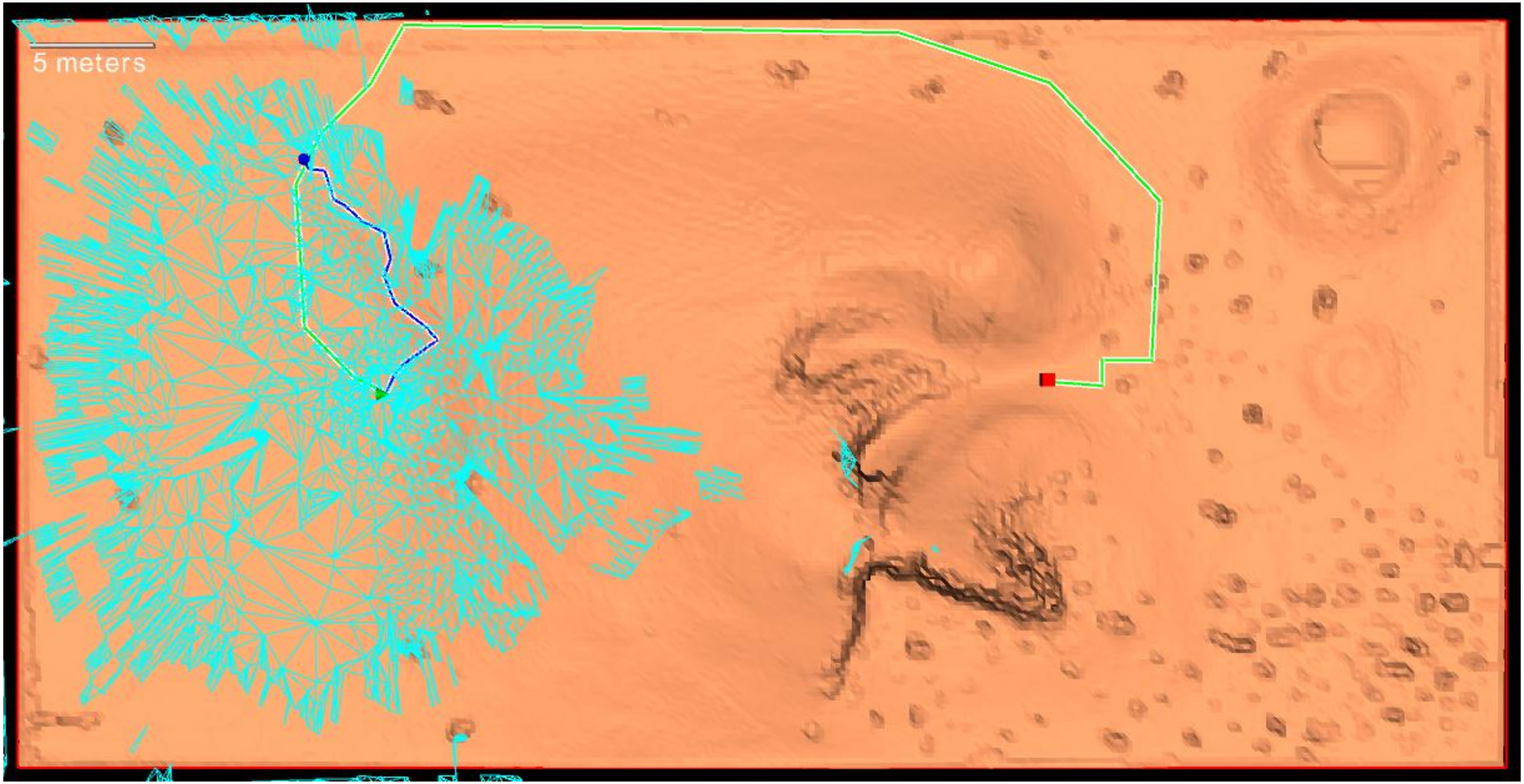

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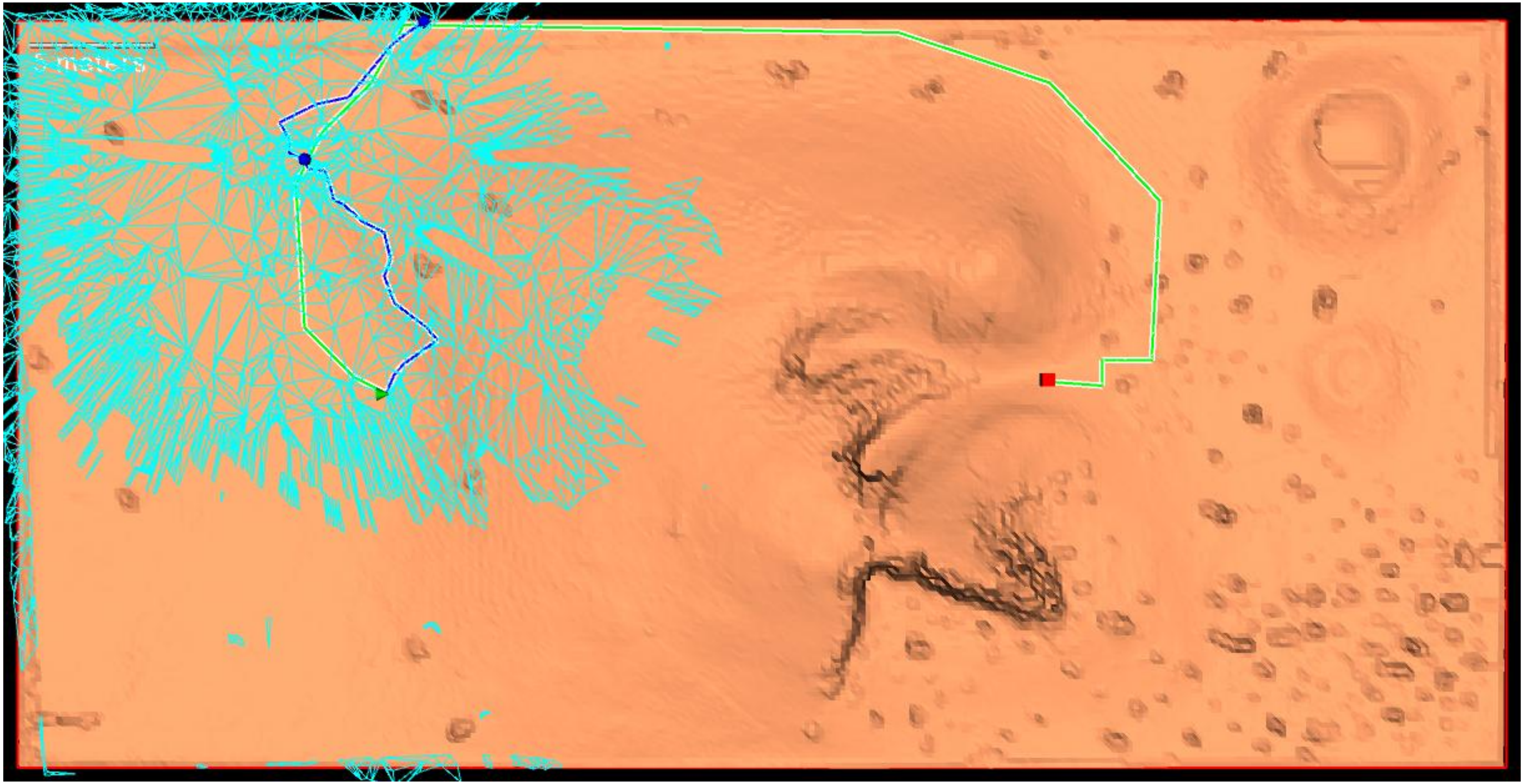

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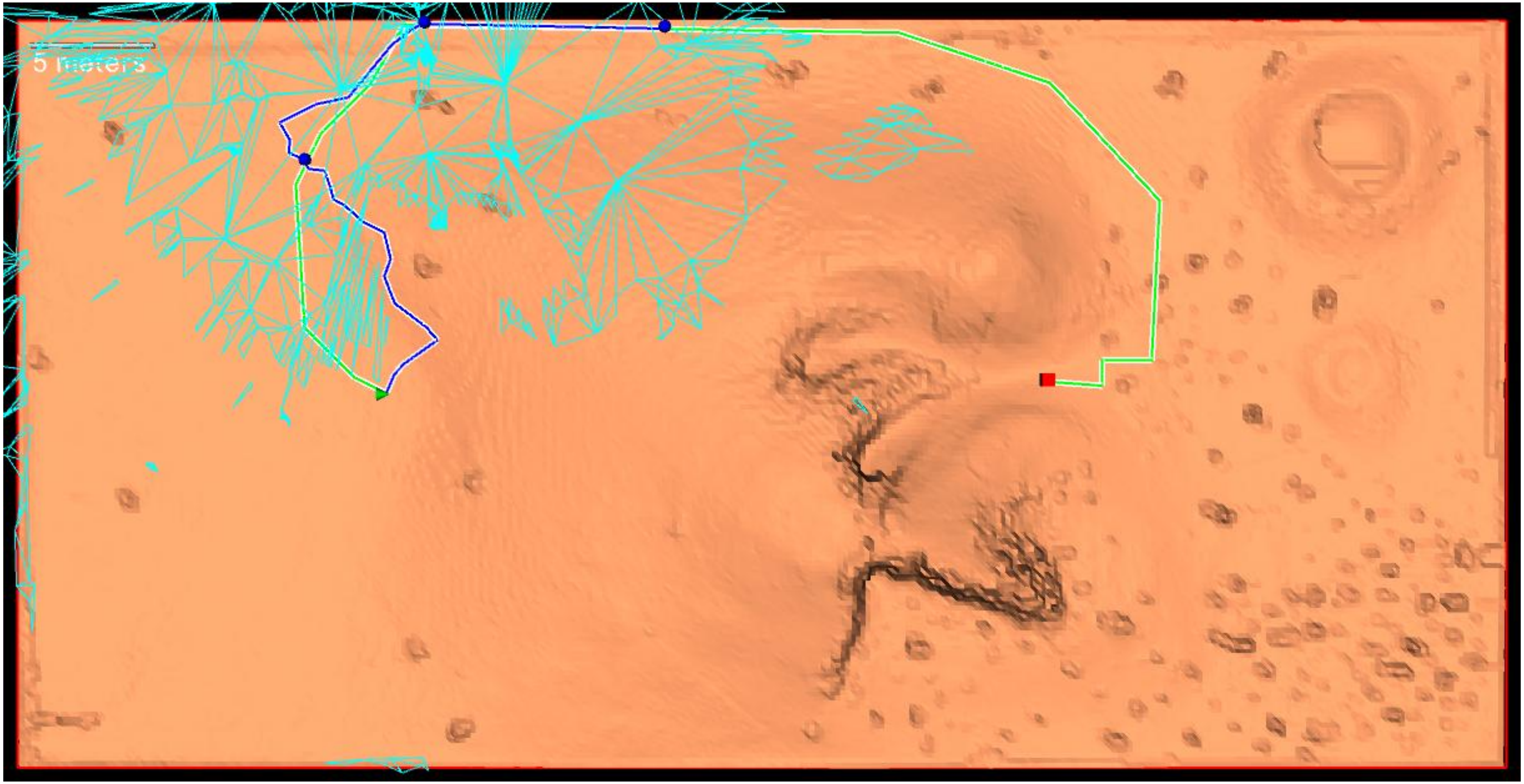

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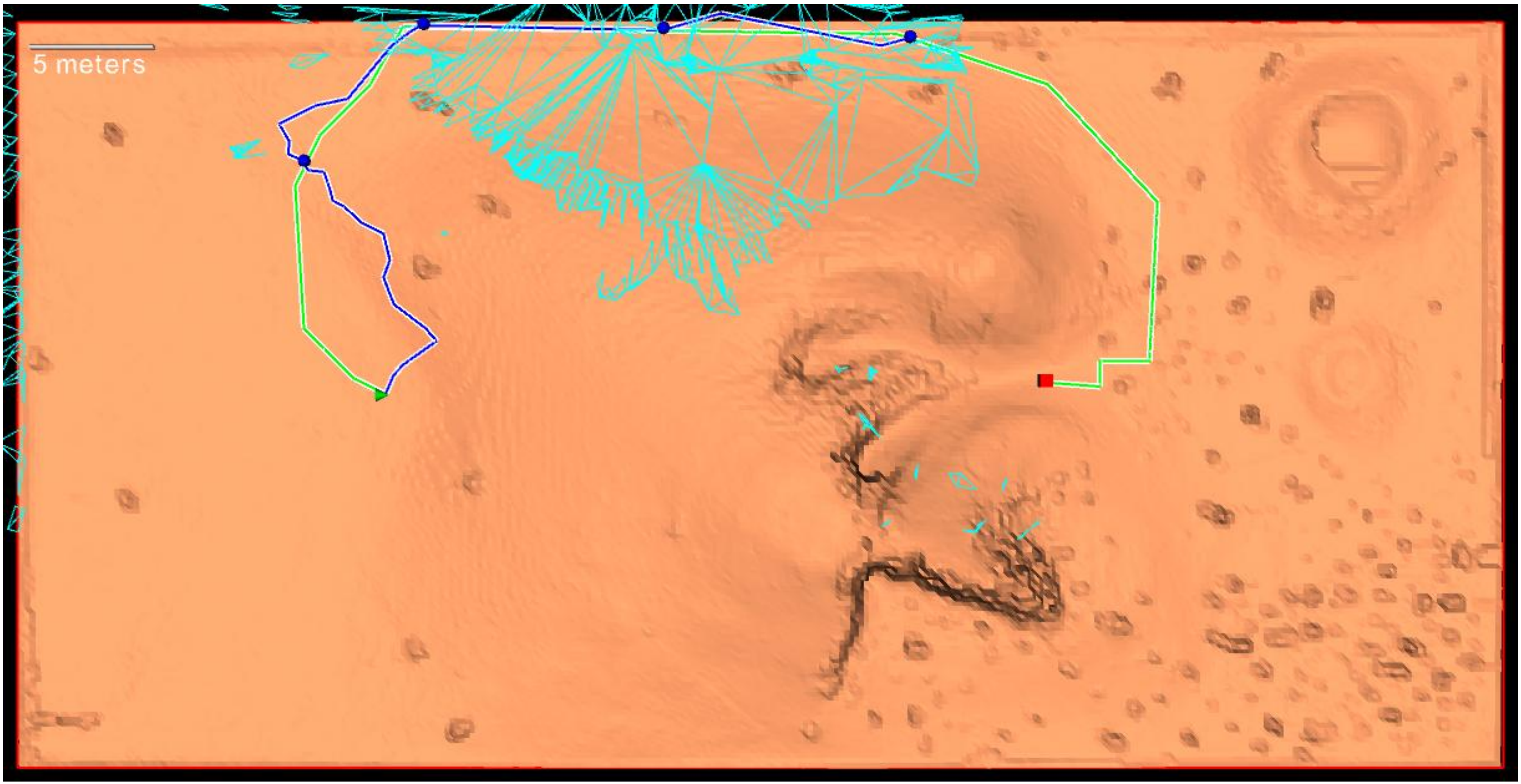

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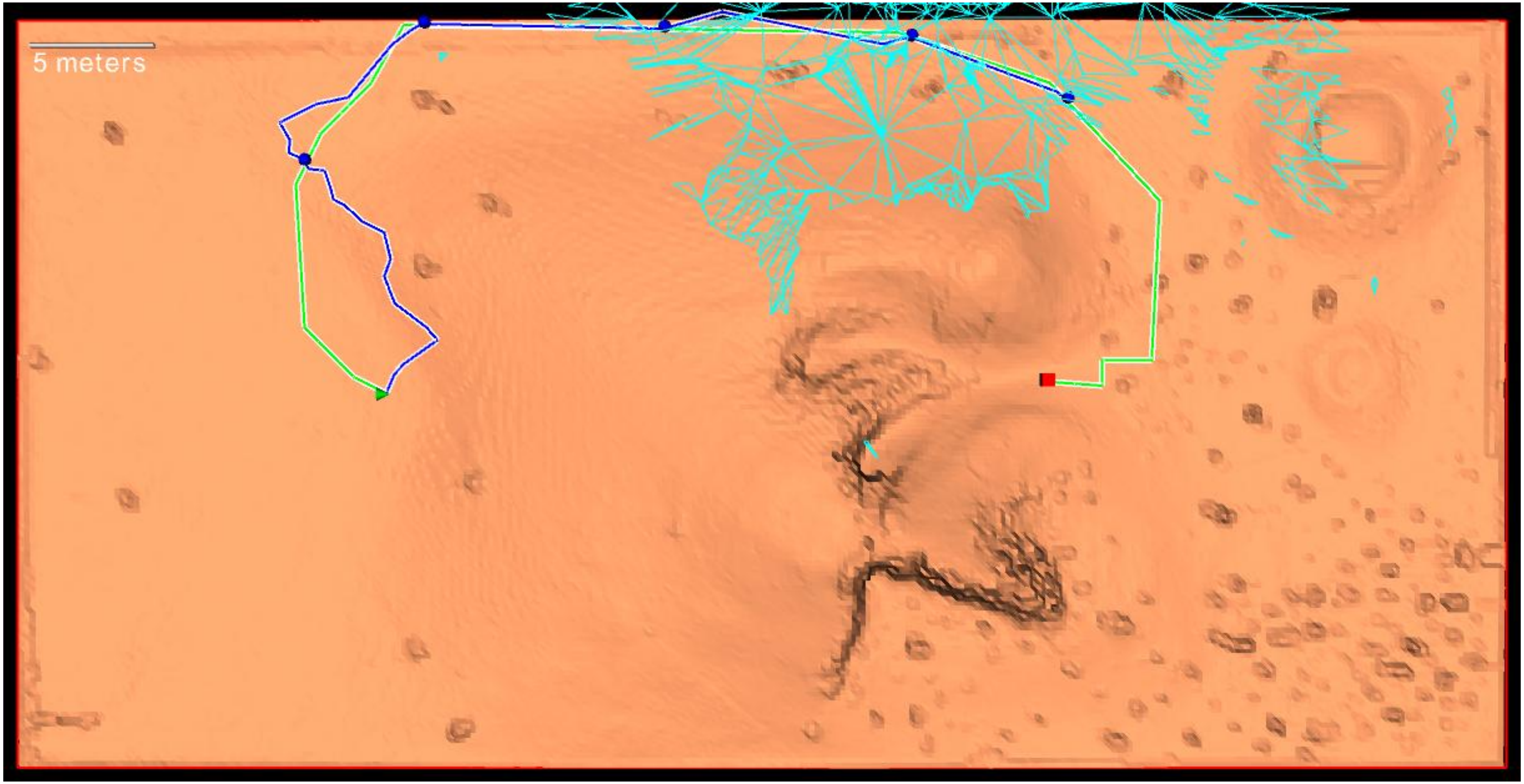

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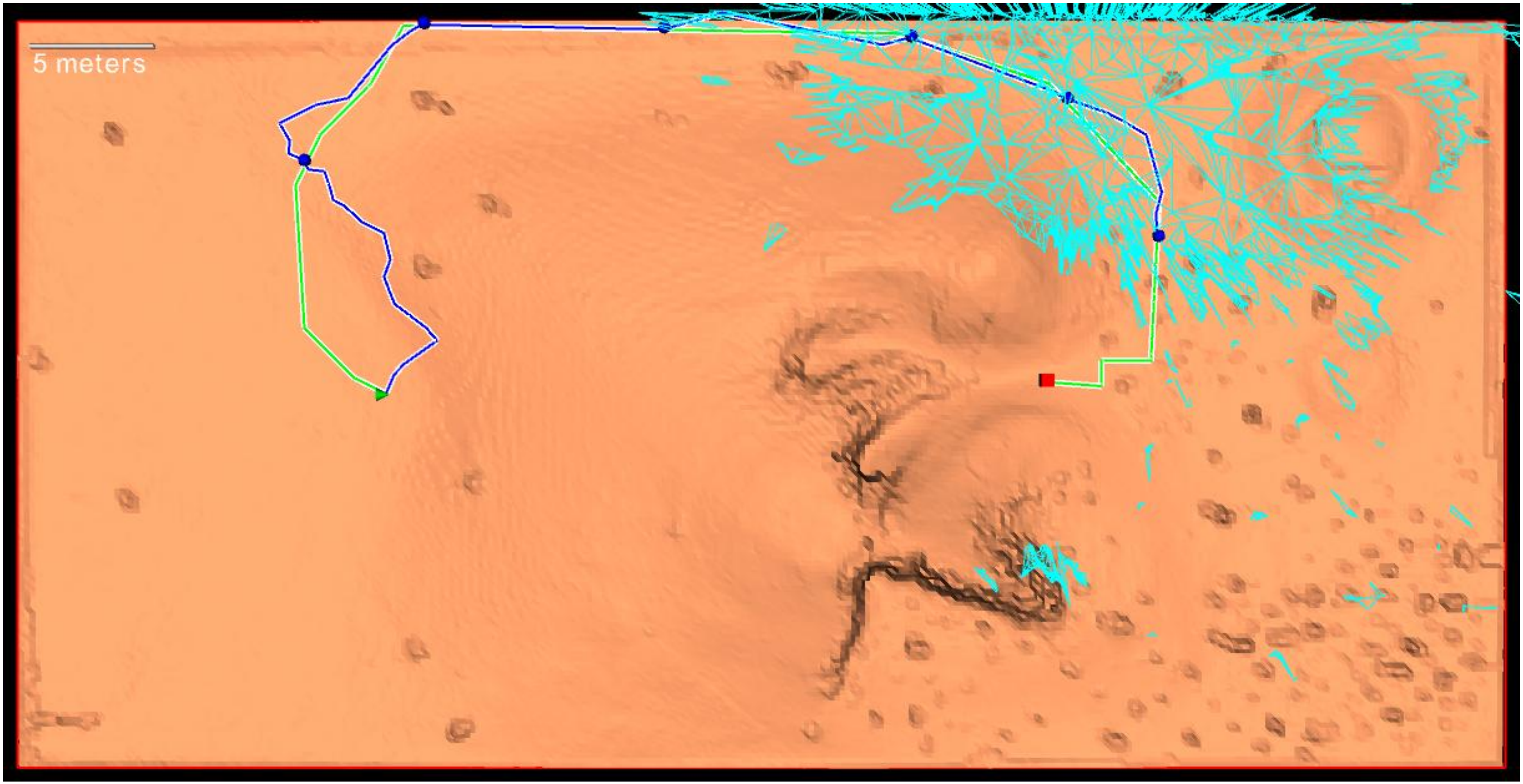

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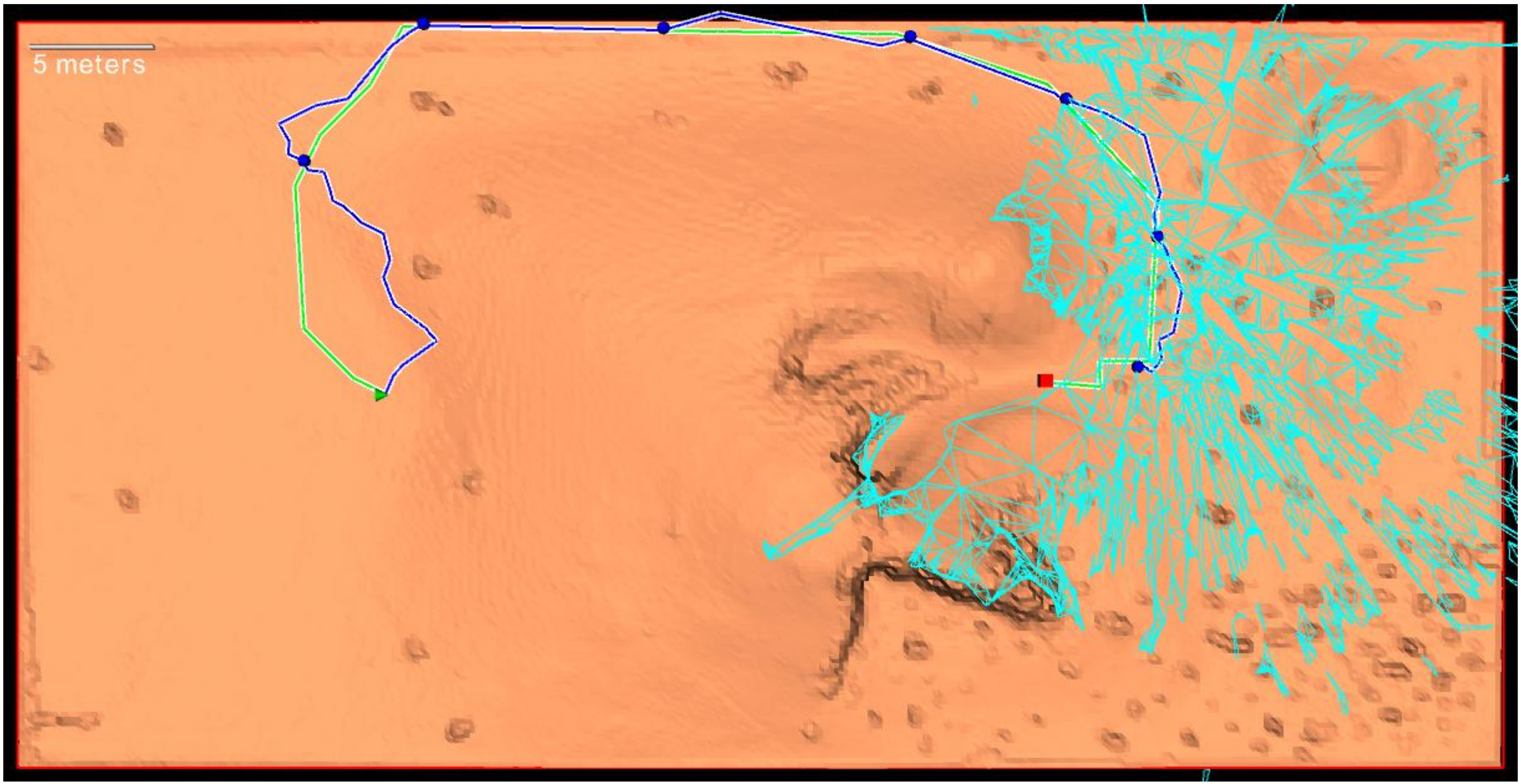

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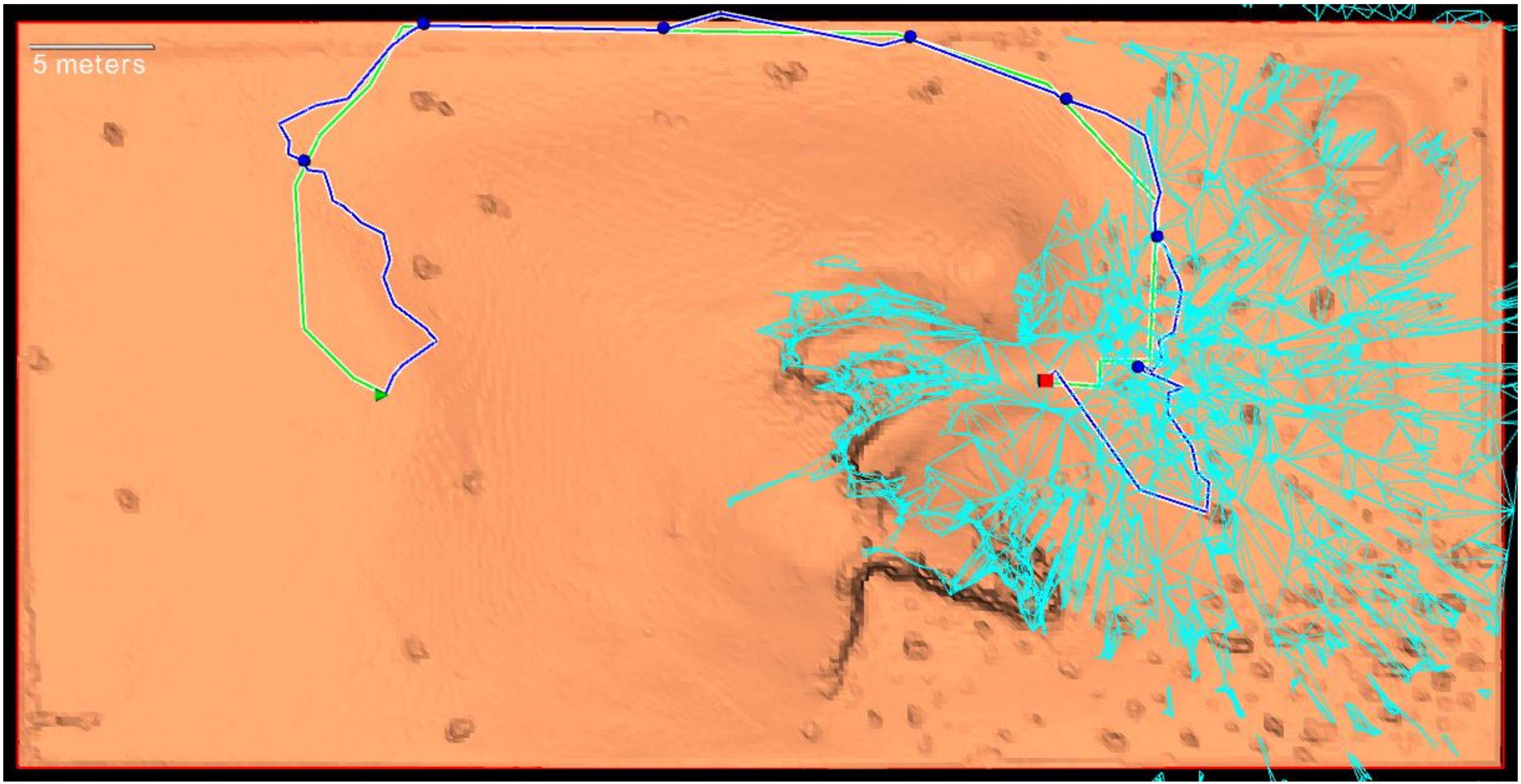

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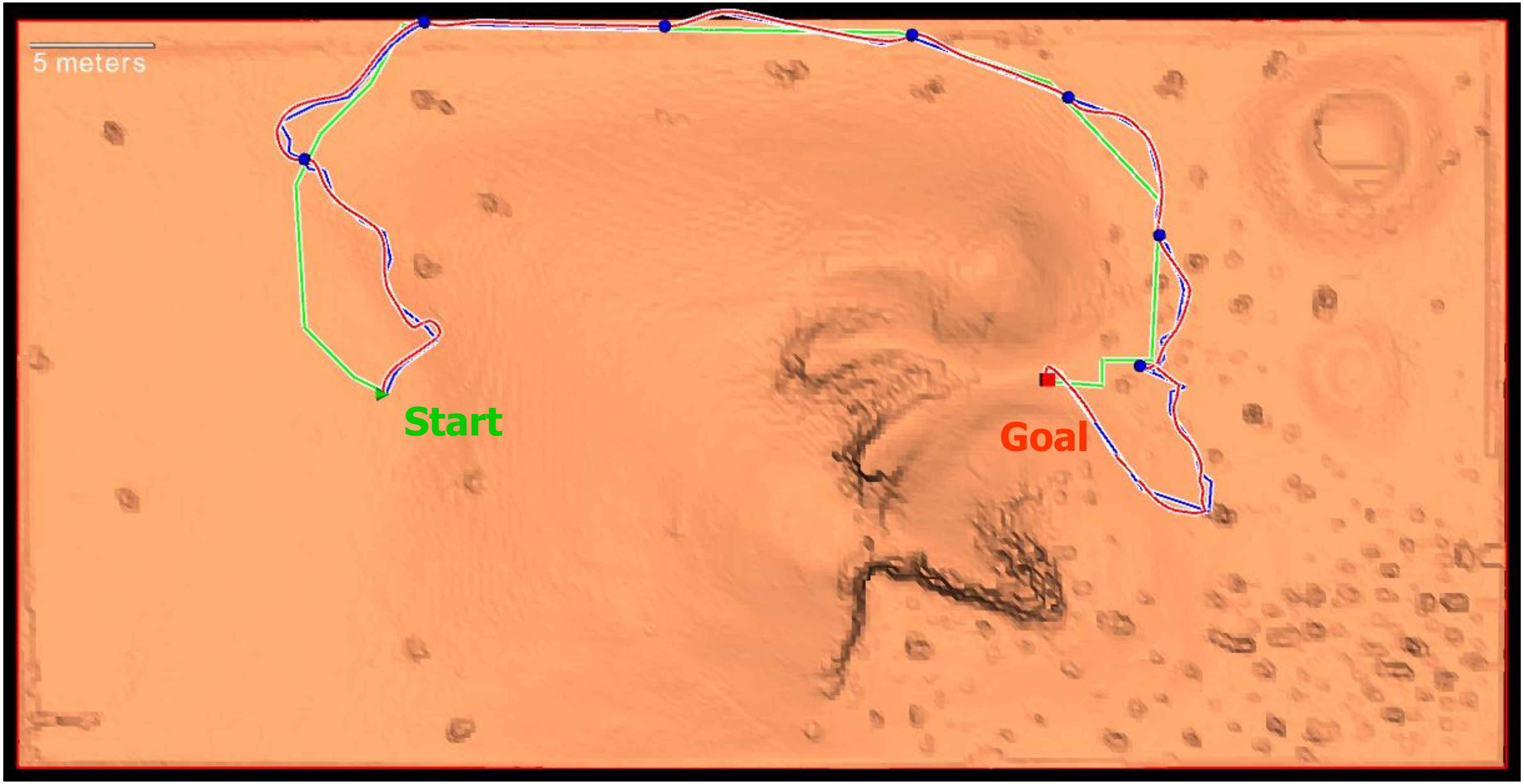

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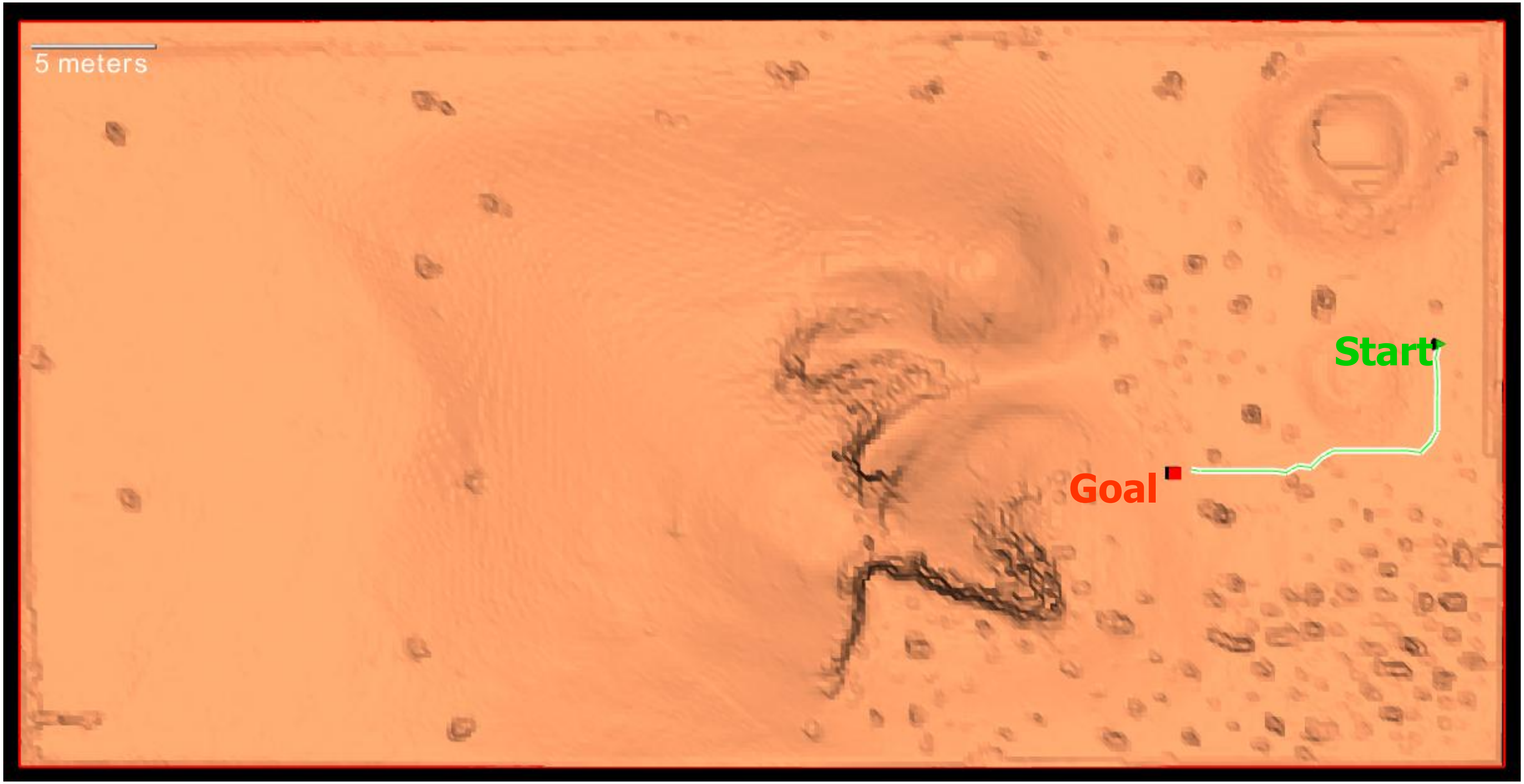

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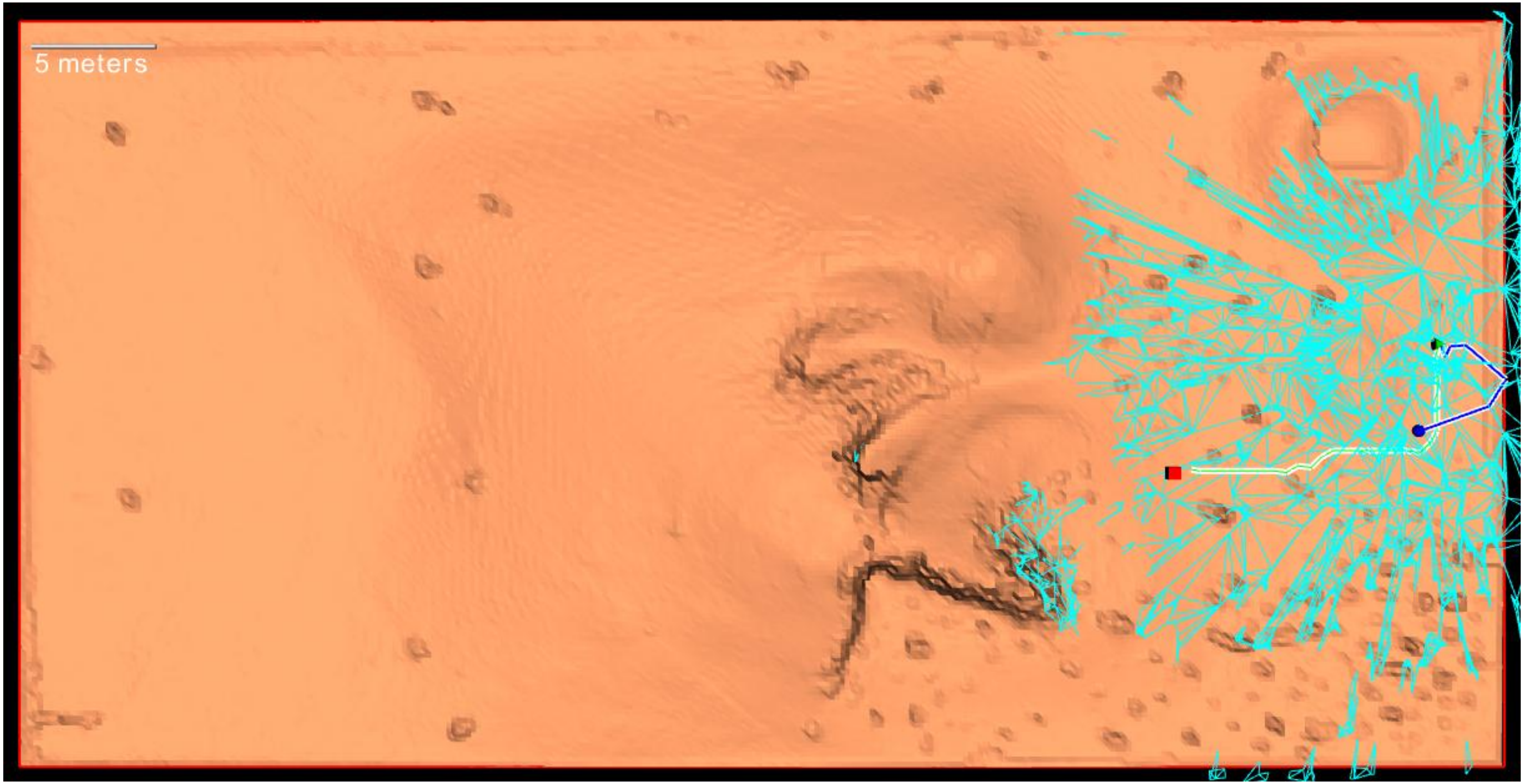

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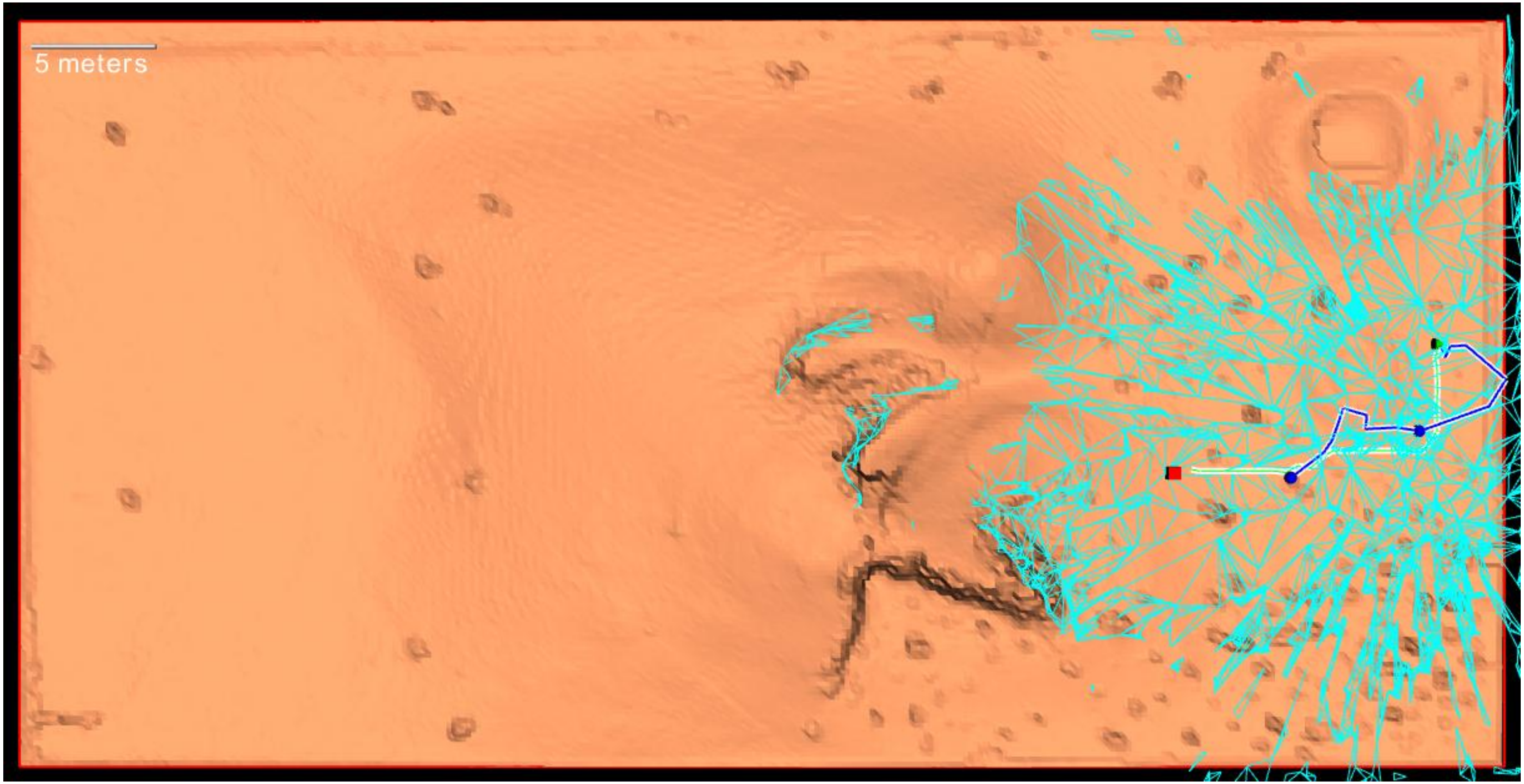

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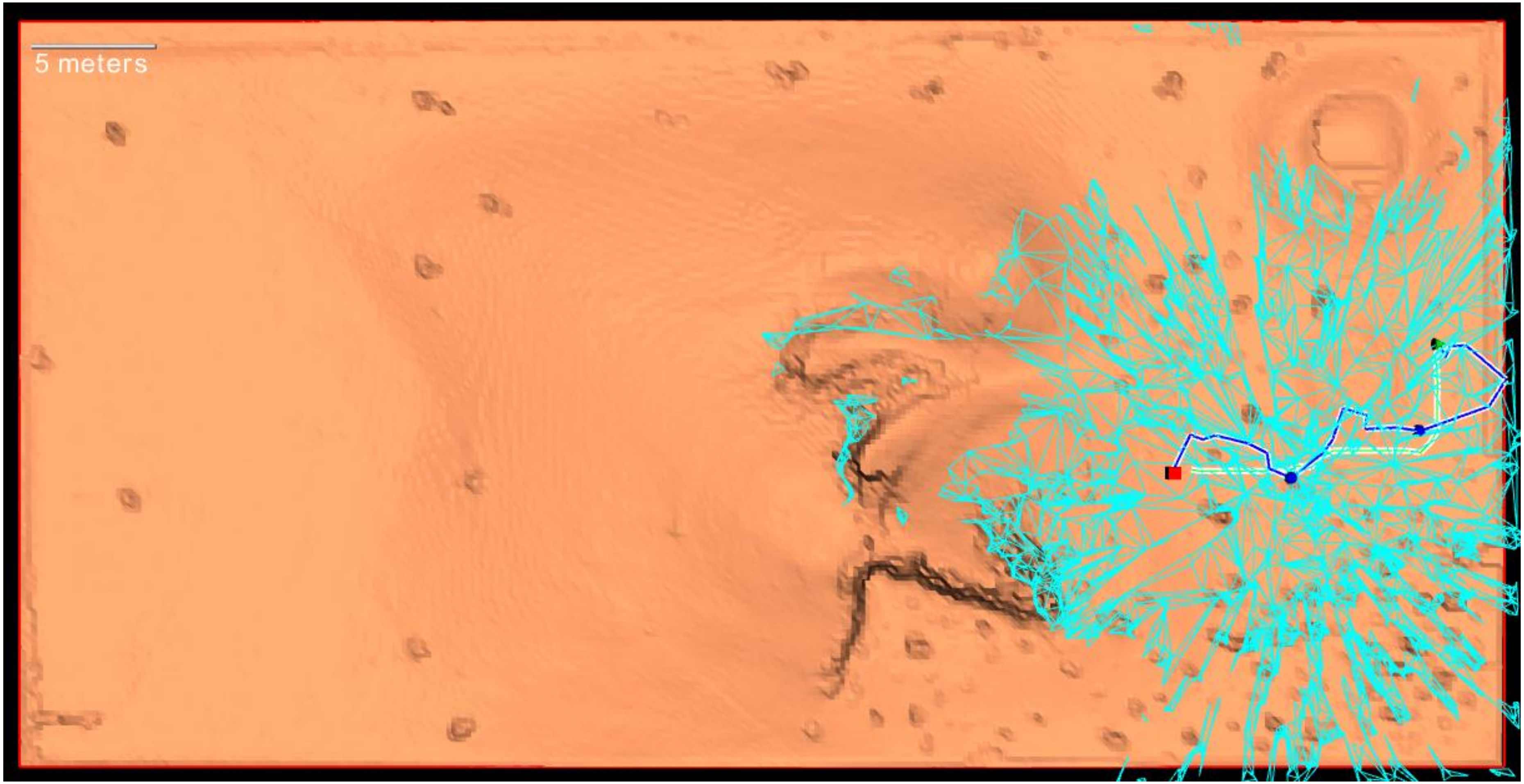

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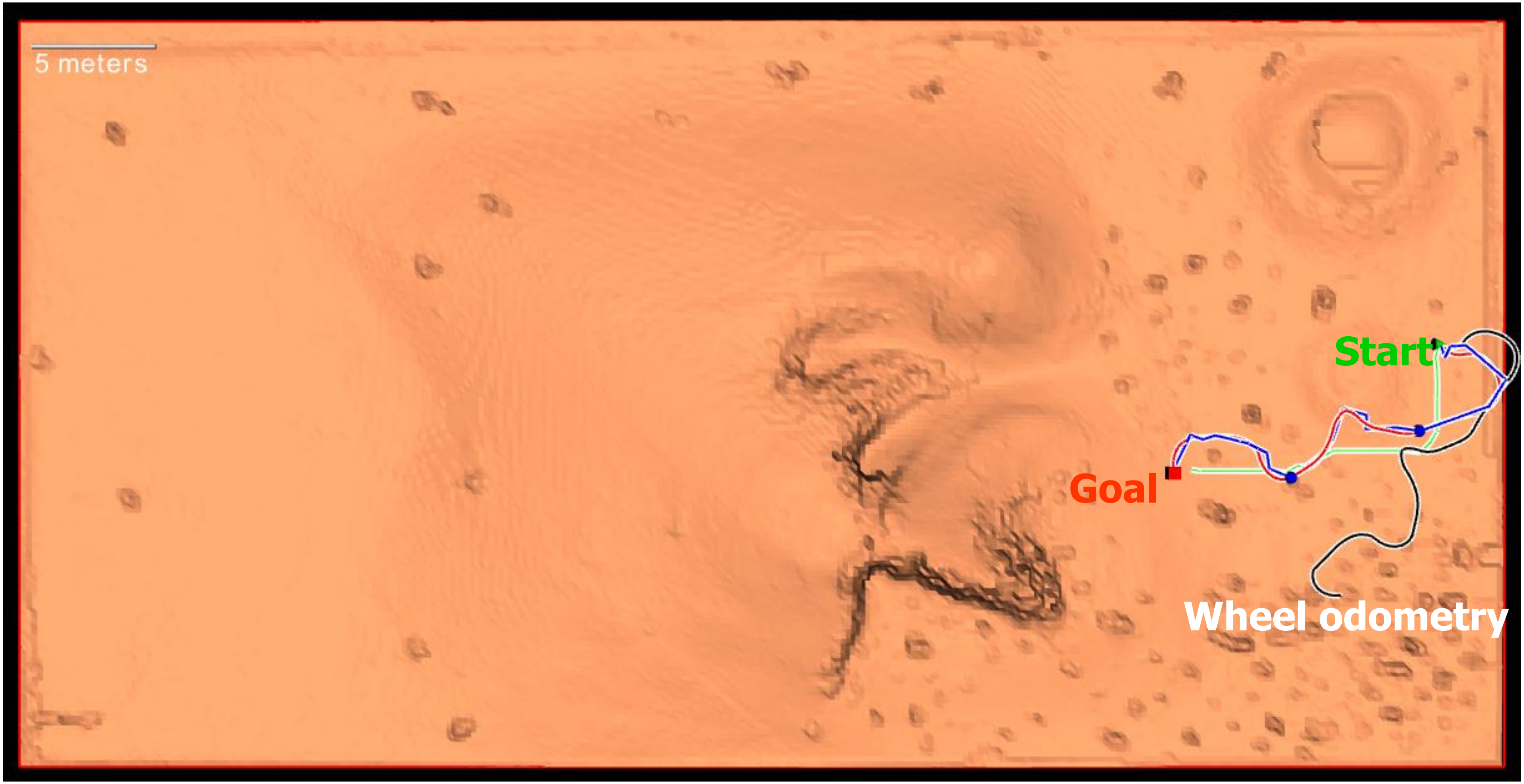

Lessons Learned

- There is a need for Localization
- Limitations in the rover capabilities
- Several components require domain specific parameters
- Extensive testing extremely useful

Future Work

- Terrain analysis
  - What does the robot sees?
    - Open area, cluttered environment, the side of a hill?
- Different mobility platforms
- State estimation:
  - Implement 6DOF KF or RBPF
- Localization
- SLAM

Conclusions

- Active vision is accurate and robust
- ITM representation is compact and accurate
- ITM useful for environmental modeling and also for path planning
- Successful Over-the-Horizon navigation an important step towards autonomy capabilities in planetary exploration

Mars Exploration Rover (NASA)