

CS-417 INTRODUCTION TO ROBOTICS AND INTELLIGENT SYSTEMS

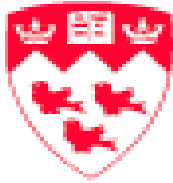
Space Robotics

On-Orbit Servicing of Satellites



Work done at the Canadian Space Agency





AUTONOMOUS CAPTURE OF A TUMBLING SATELLITE

Guy Rouleau, Ioannis Rekleitis, Régent L'Archevêque,
Eric Martin, Kouros Parsa, and Erick Dupuis

**Space Technologies
Canadian Space Agency
Montréal, Canada**

Presented at the 2006 International Conference on
Robotics and Automation

Ioannis Rekleitis

Motivation

- More than 10K objects bigger than 10cm in orbit
- More than 280 satellites currently in GEO orbit
- The life span of a satellite is around 10 years
- The cost of sending even a small satellite is \$10M

SOLUTION

- Use a servicing satellite to extend the life of a satellite or to de-orbit an object

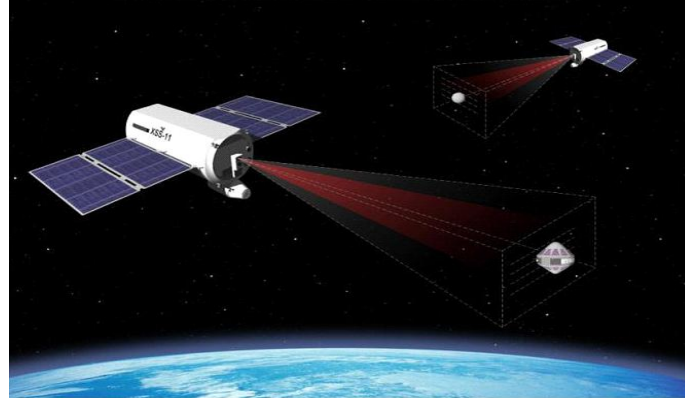


On-Orbit Servicing Opportunities

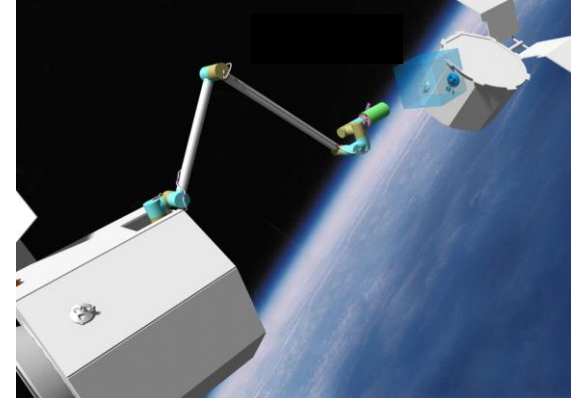
- OOS missions with Canadian involvement



Shuttle Return to Flight



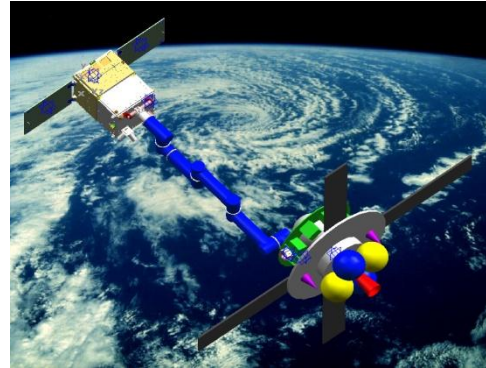
XSS-11



Orbital Express



Hubble servicing study



TECSAS



MBS, Canadarm2, Dextre



OOS Related Missions

(examples)

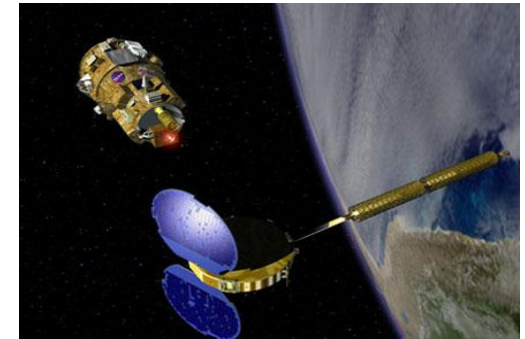
Russian Progress Vehicle



Japan ETS-7 Mission



NASA DART Mission



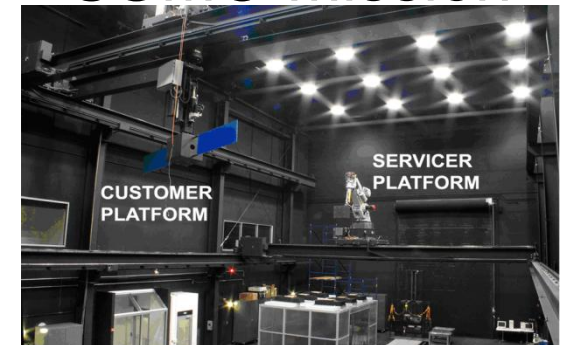
ESA ATV Mission



CX-OLEV Mission

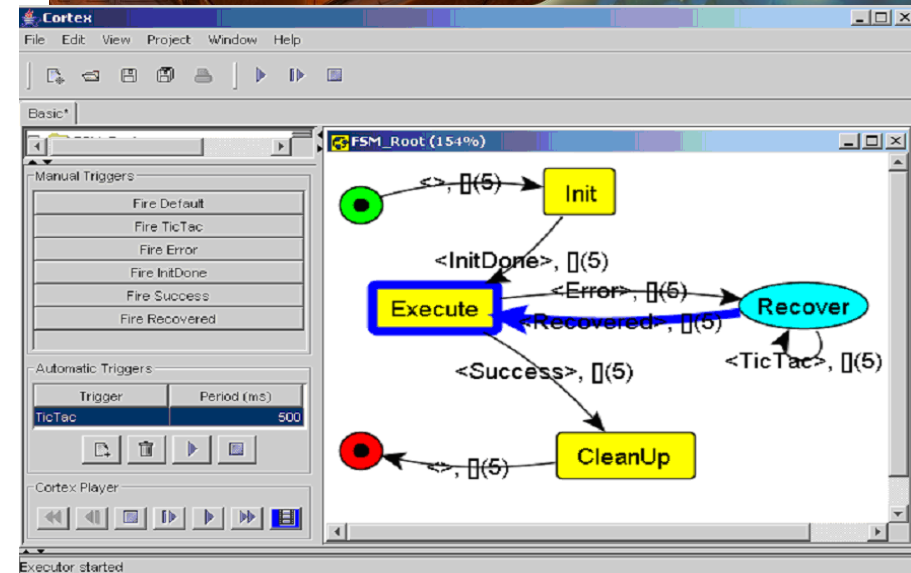
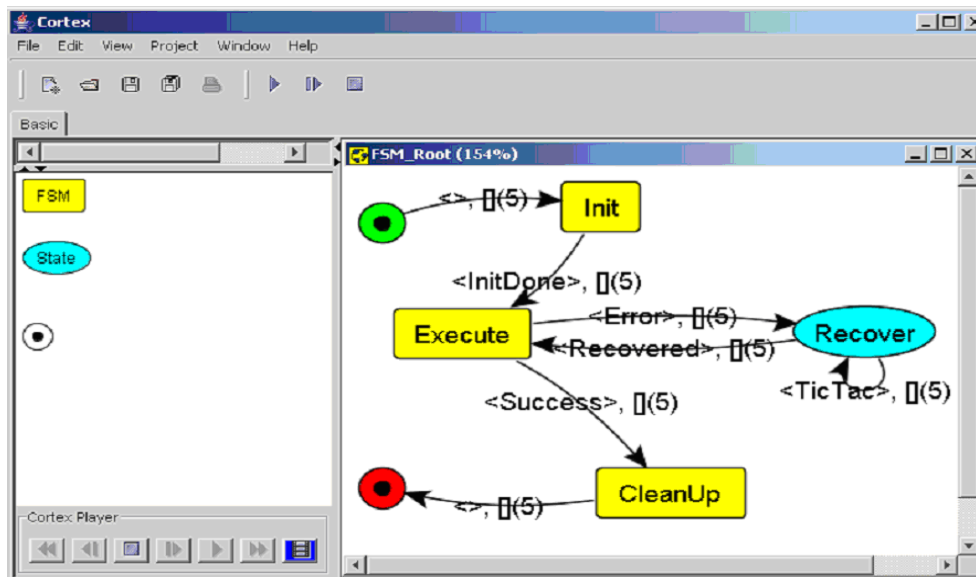


DARPA NRL SUMO Mission

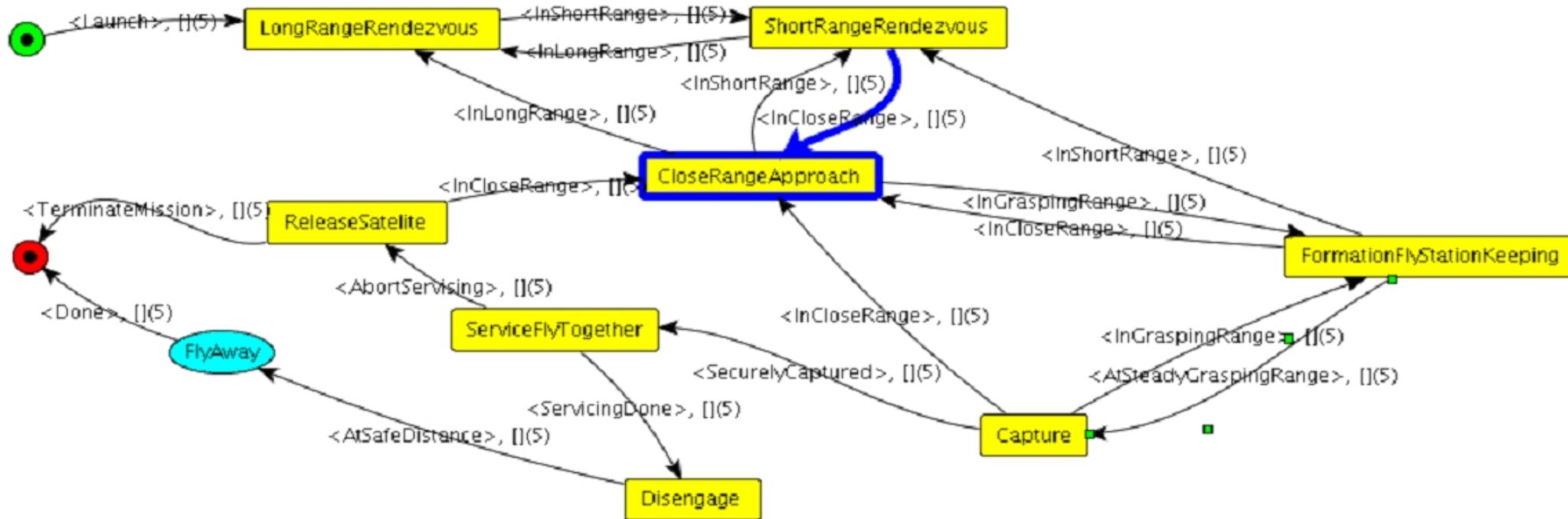


Autonomous Control

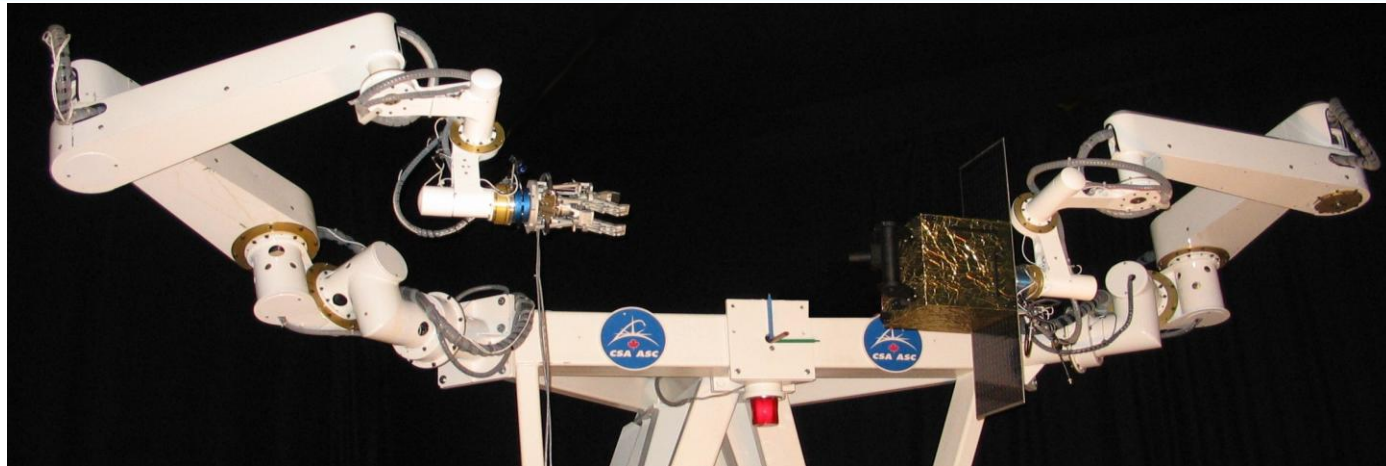
- Toolbox for Reactive Autonomy
- Hierarchical Finite State Machines



High-Level Scenario

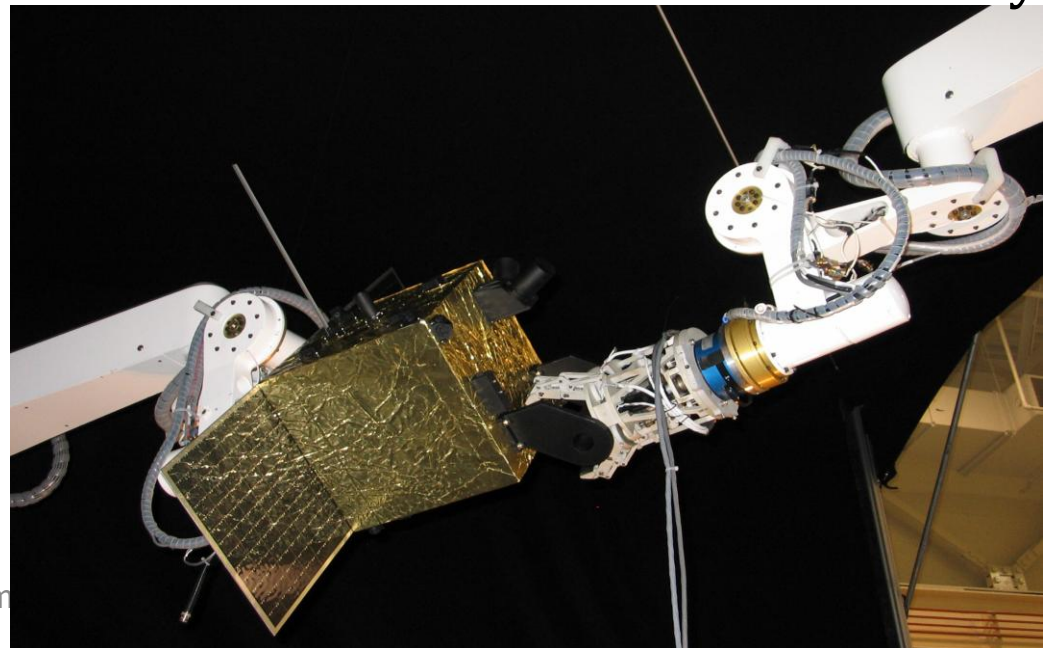


Laboratory Setup

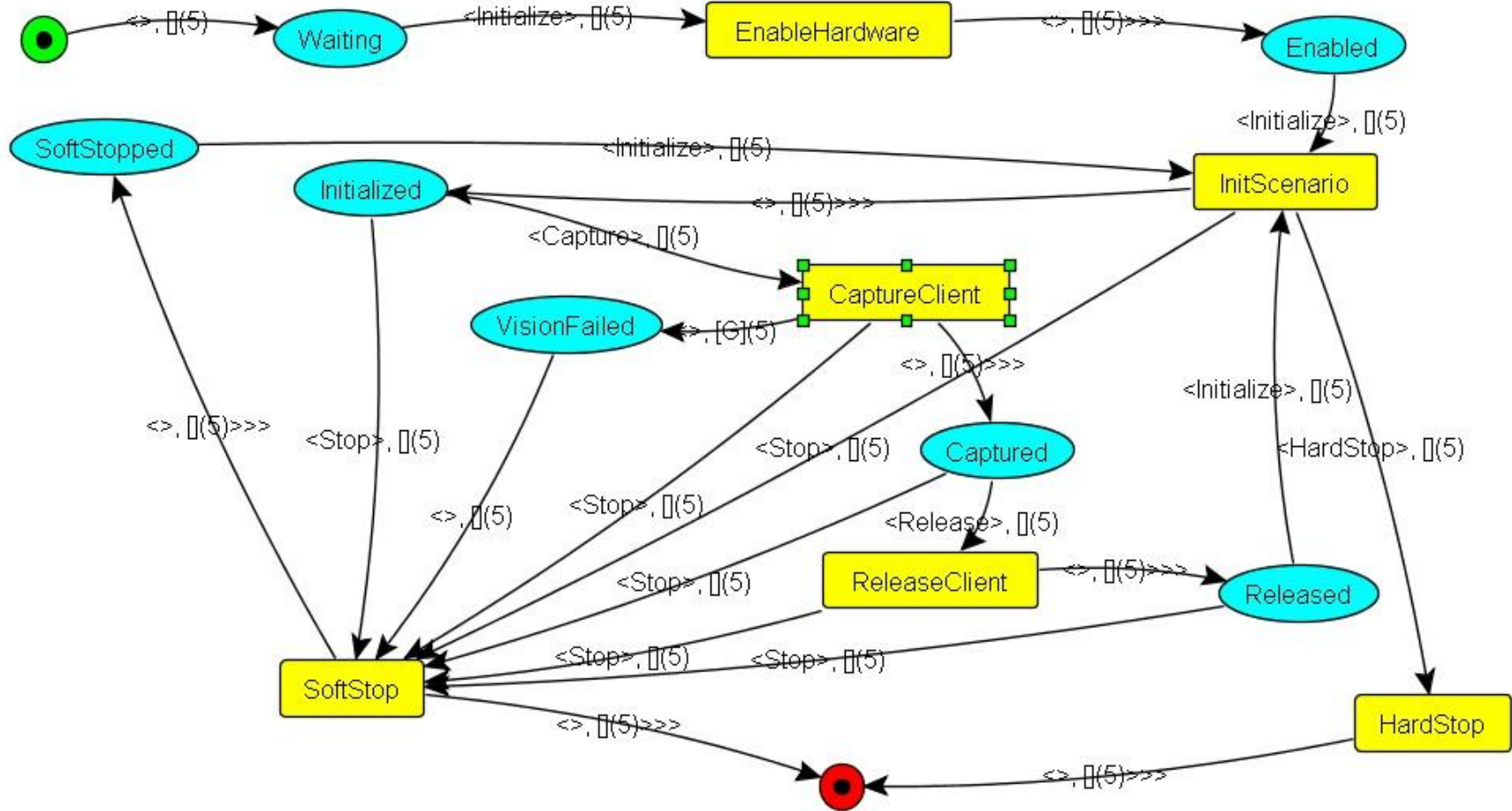


The SARAH hand from Laval University

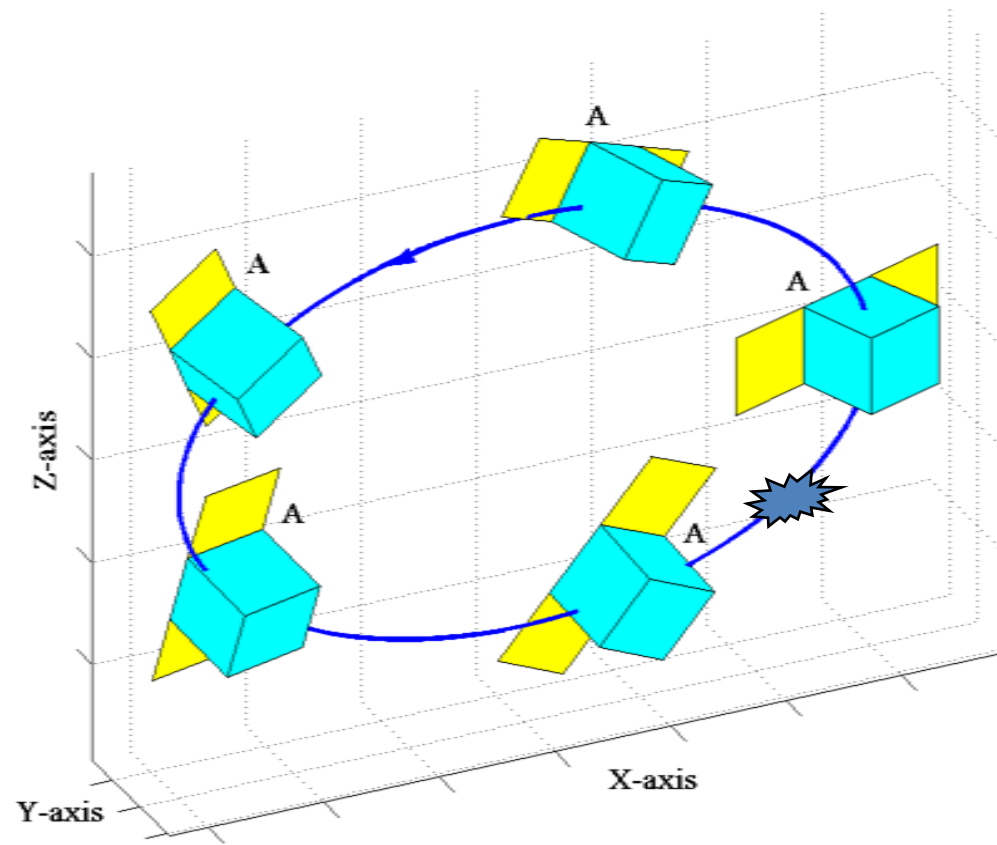
Laser Camera System
(LCS), Cape S/W
from Neptec



Autonomous Capture

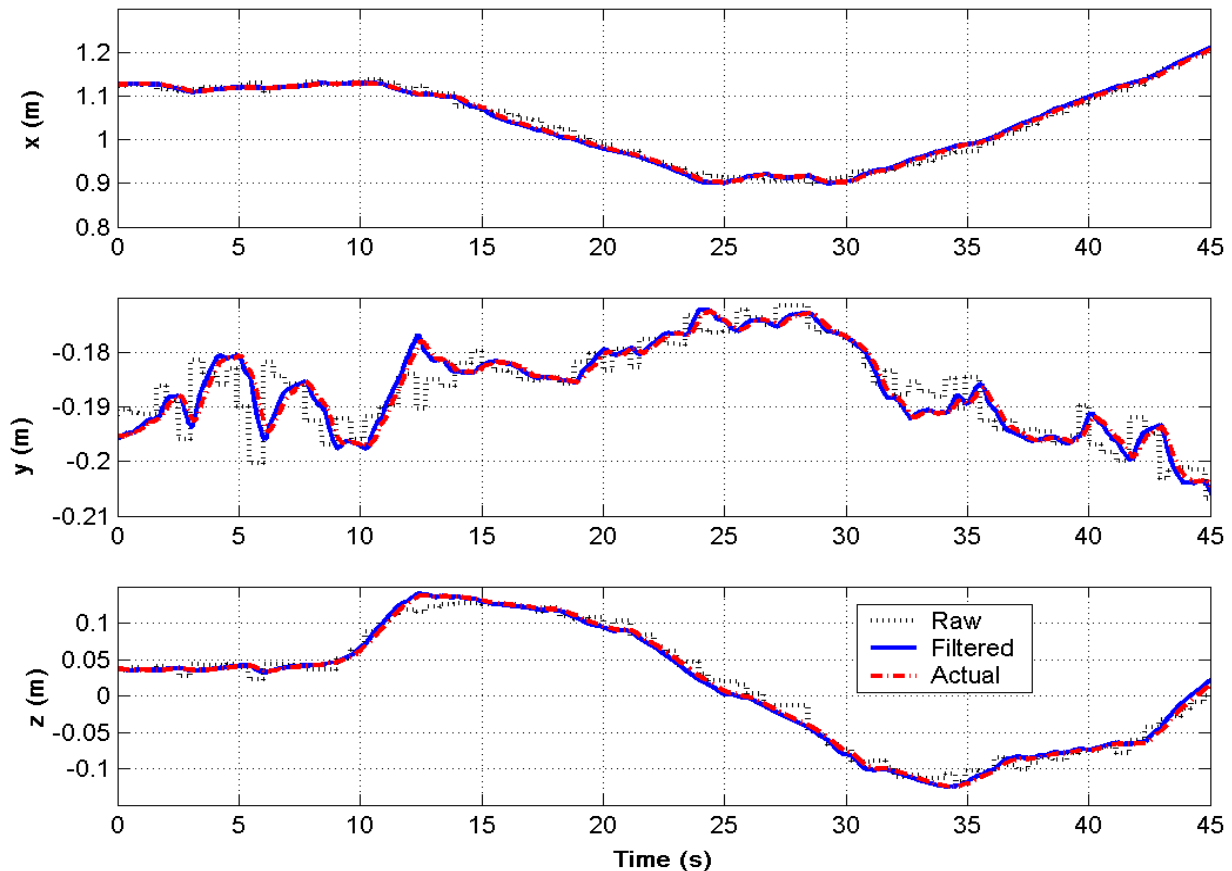


Trajectory Generation of the Target Satellite



Tracking

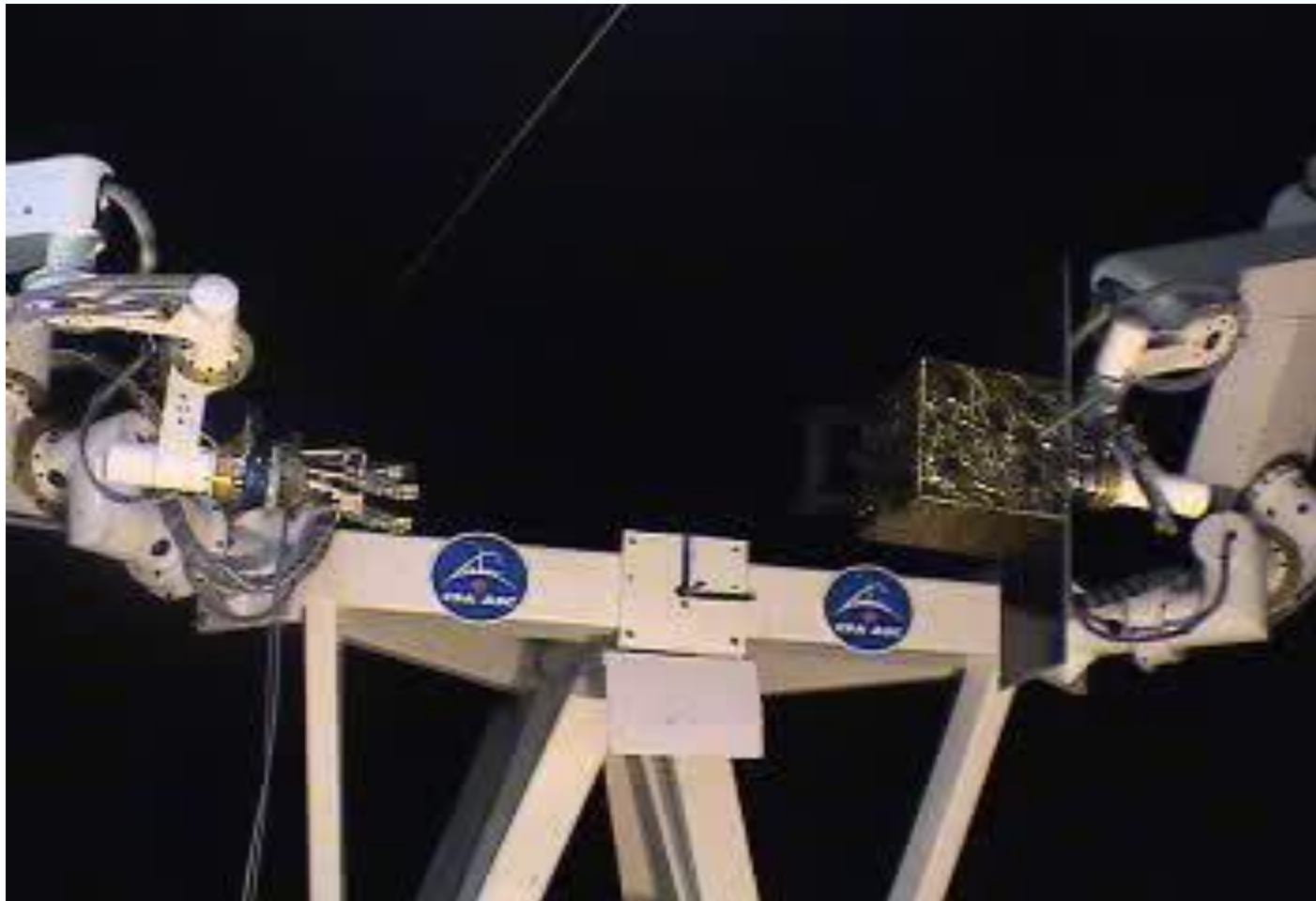
- A standard implementation of an extended Kalman Filter is used to track the pose of the target satellite
- Signal at 2Hz
- Delay of 1 step
- EKF prediction of 1 step



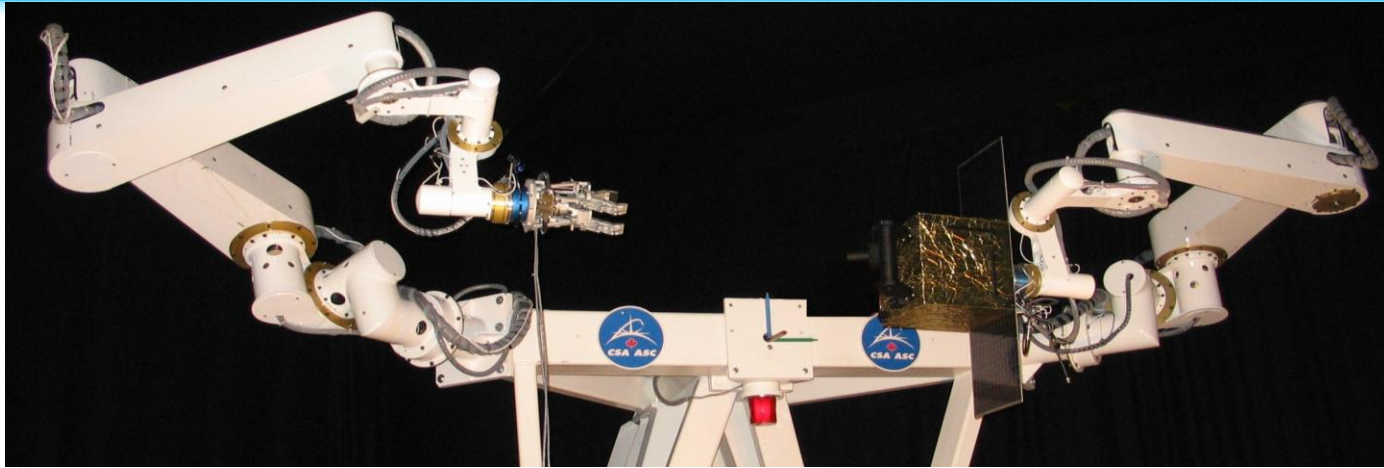
Tracking



Capture



Main Accomplishments



- Autonomous capture of a tumbling satellite
- Transatlantic monitoring and operation of the capture procedure
- Emulate the motion of a tumbling satellite using a 7-DOF manipulator



Conclusions

- Cortex greatly facilitated the creation of autonomy scenarios
- The LCS from Neptec provided robust pose estimation (varying illumination conditions, obstructions)
- First step of autonomous capture in a laboratory setting



Planetary Exploration:



- **Autonomous Over-the-Horizon Navigation**



Outline

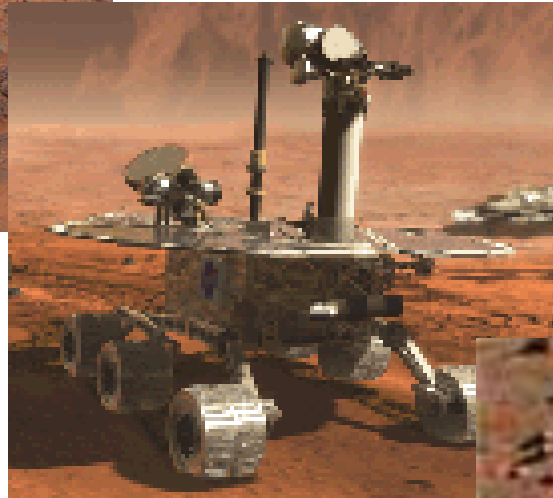
- Mars Exploration
- Background
- Main Blocks are: Terrain Modeling, Path Planning, Motion
- Control Tests from 2006 and 2007



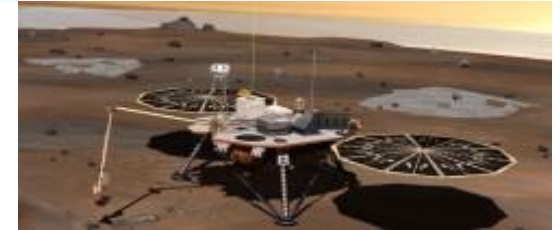
Exploring Mars



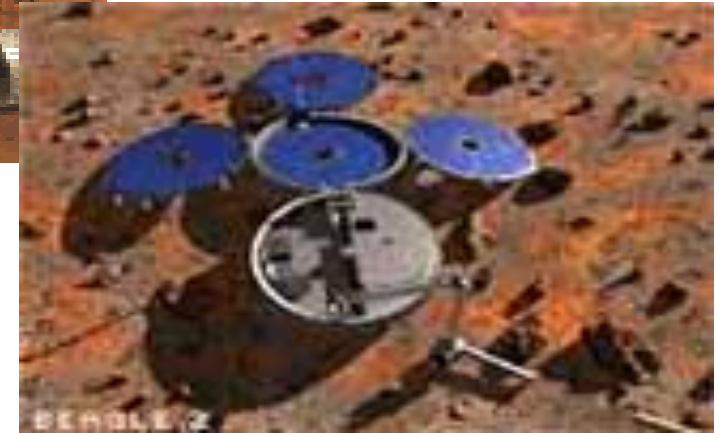
Sojourner



Spirit



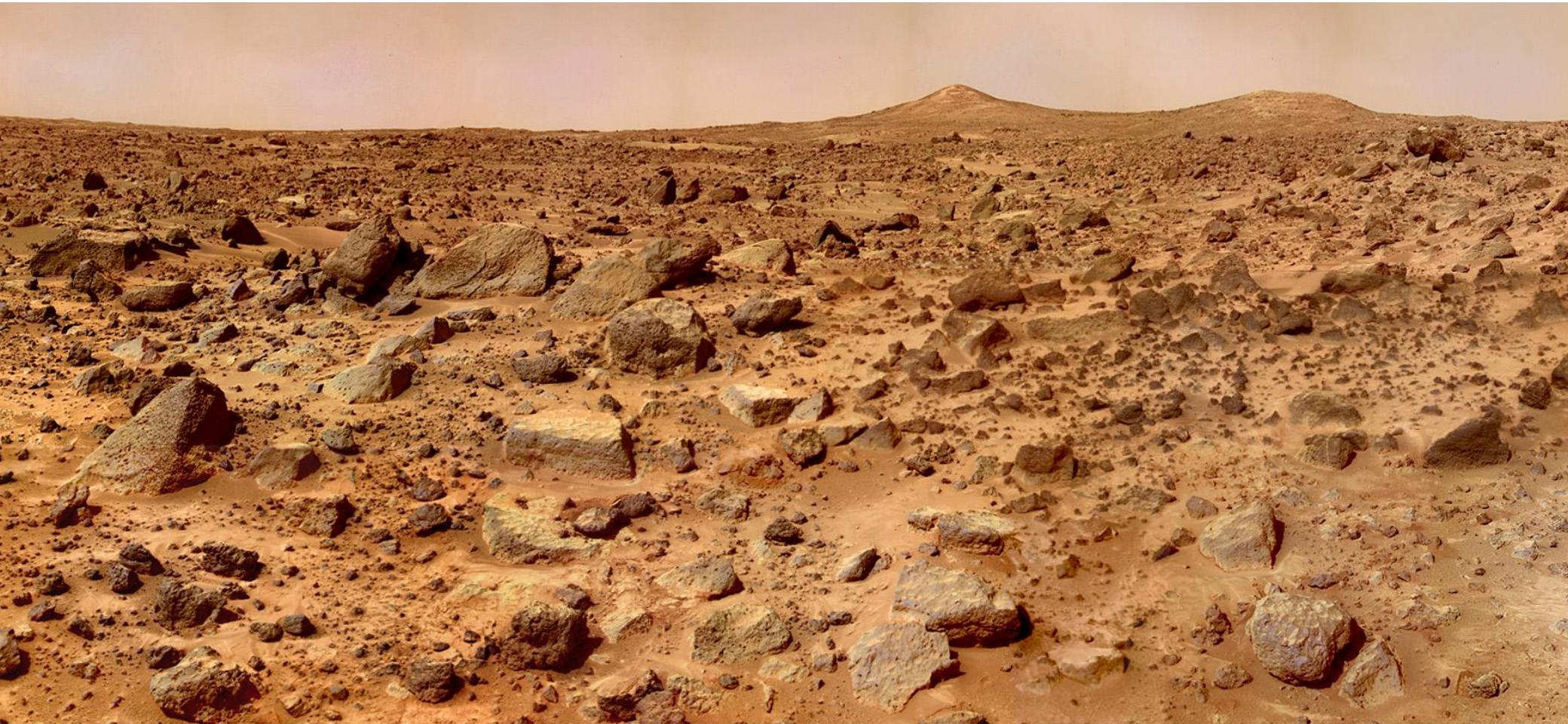
Phoenix



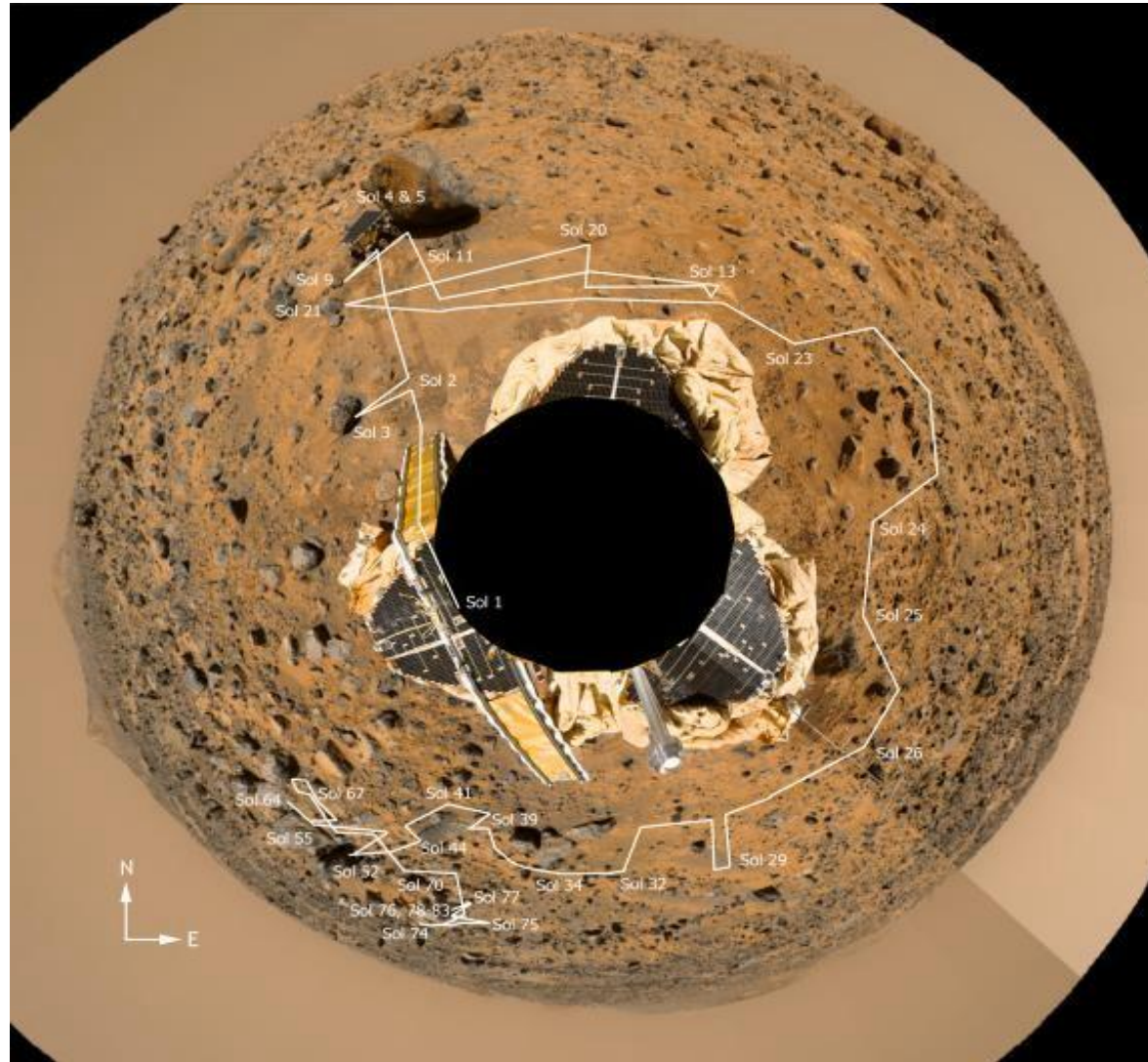
Beagle II



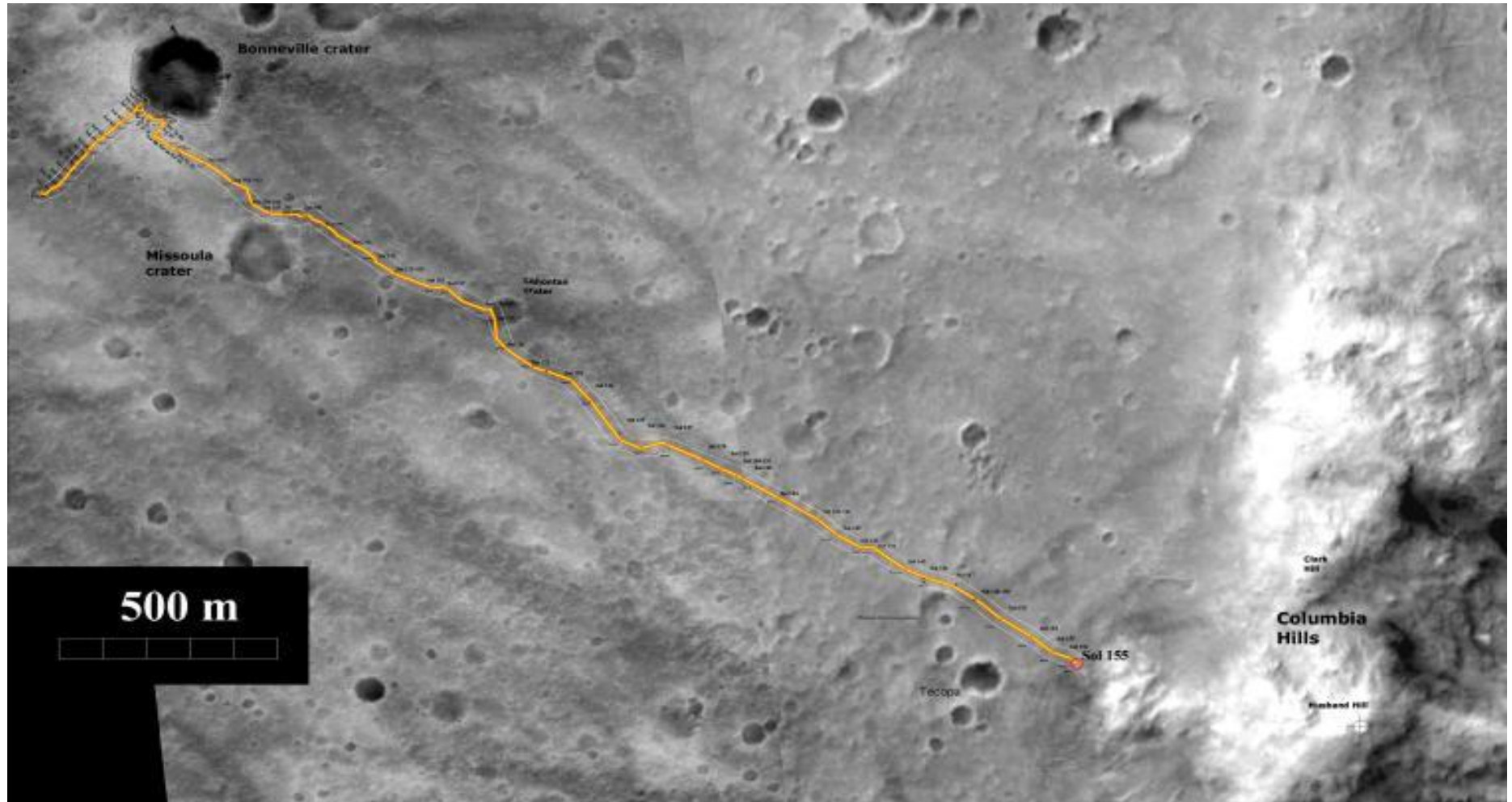
View from Sojourner



Missions - Pathfinder 1997

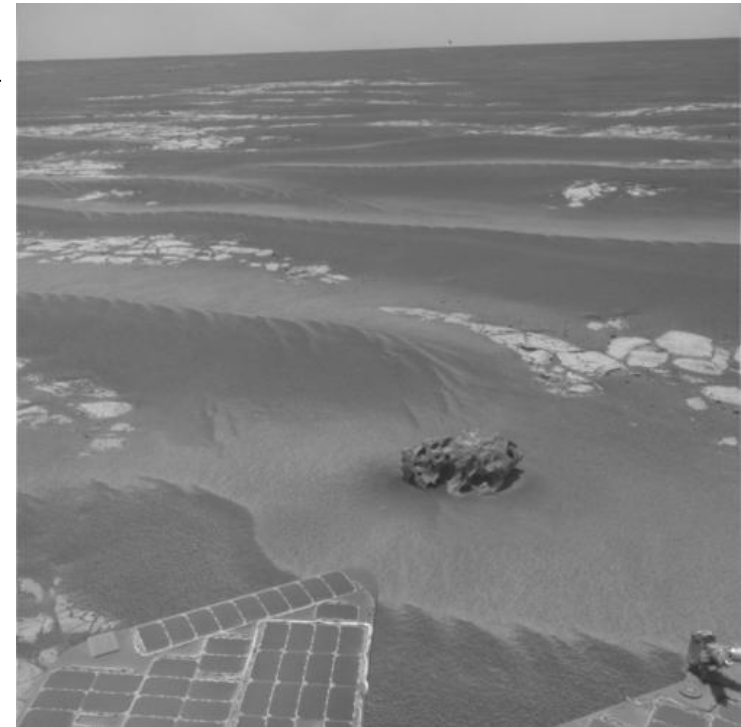


Missions – Spirit: Day 155

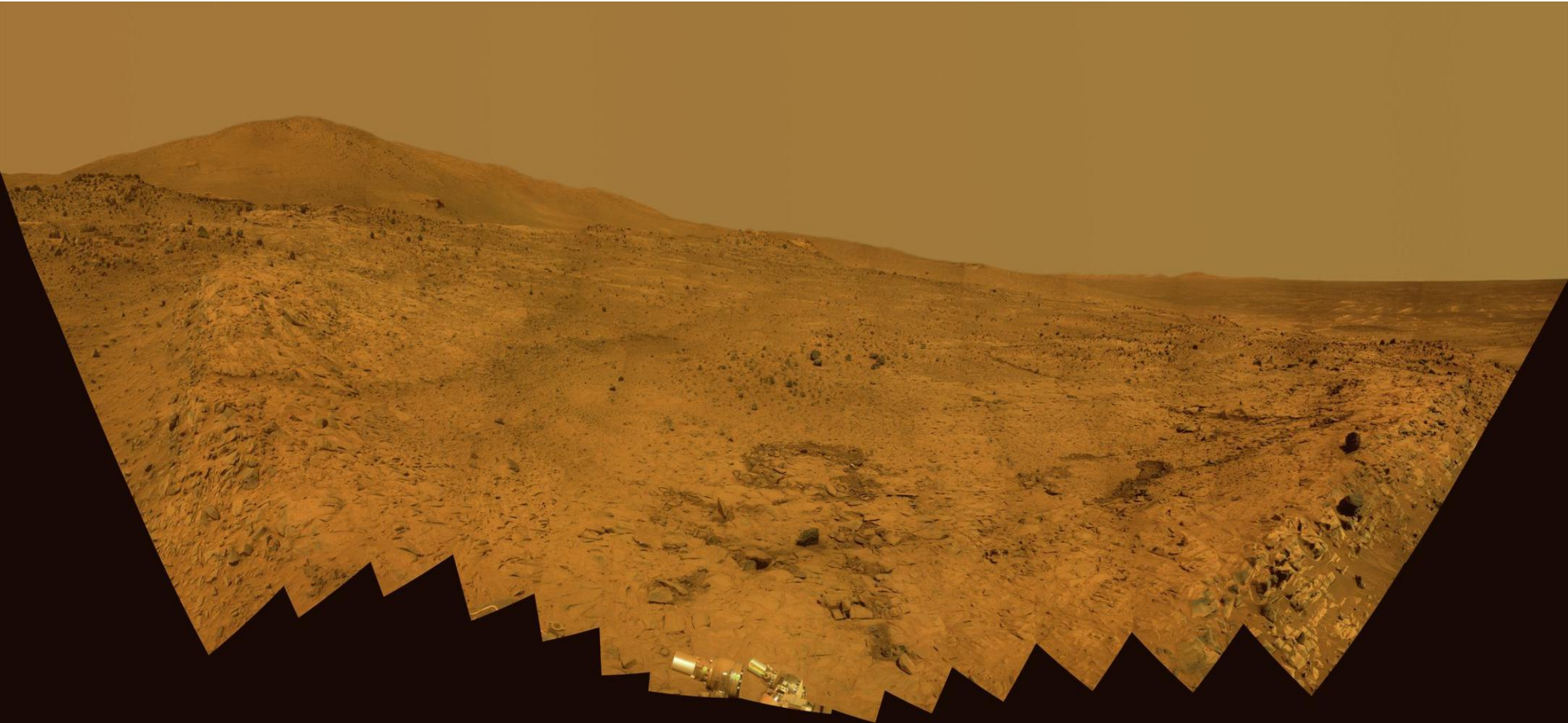


More Current Data

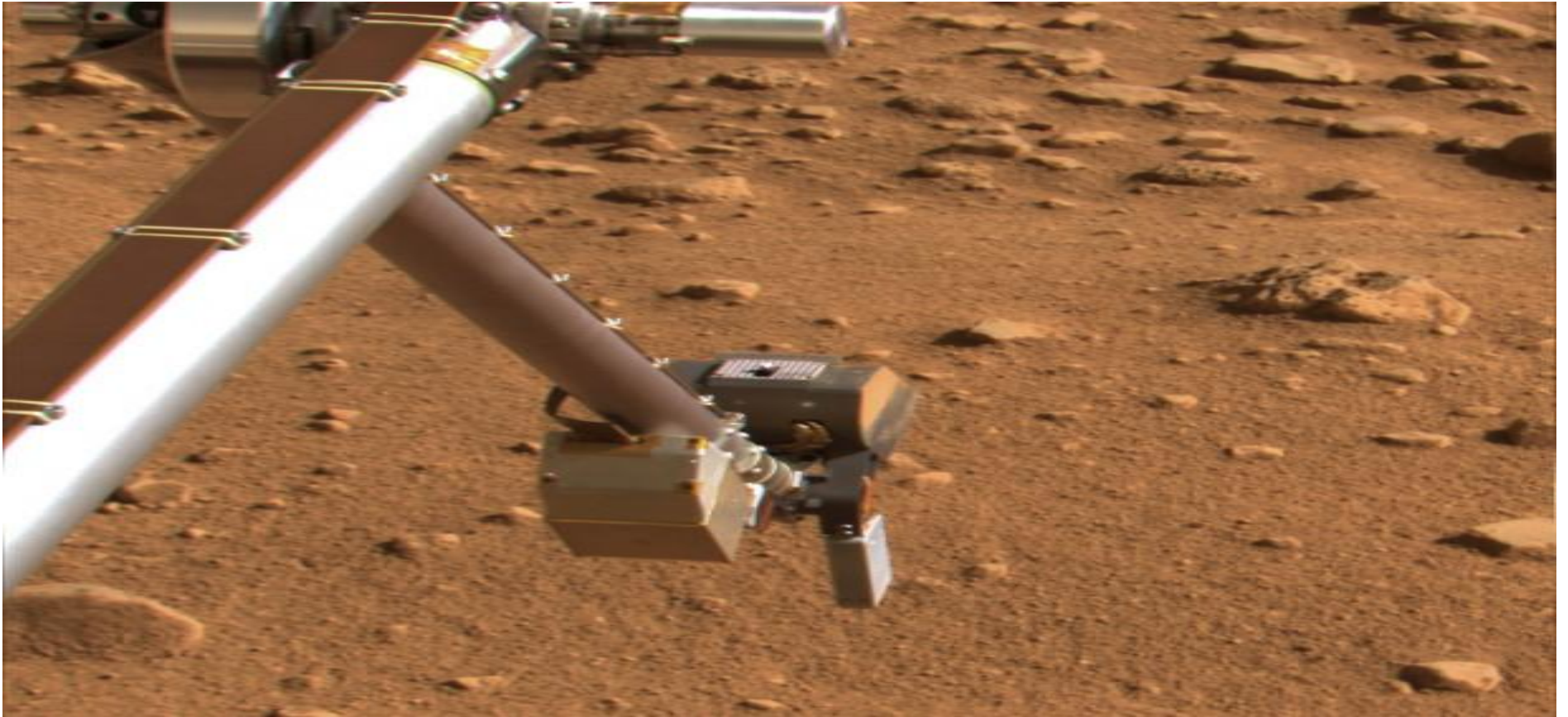
- As of Sol 2055 (Oct. 14, 2009), Spirit's total odometry remains at 7,729.93 meters (4.80 miles).
- As of Sol 2049 (Oct. 29, 2009), Opportunity's total odometry is 18,622.44 meters (11.57 miles).
- 2,022nd sol, (Oct. 1, 2009) Opportunity found another meteorite.
- Spirit is trapped in a sand pit.



A Panorama from Spirit



Phoenix in action

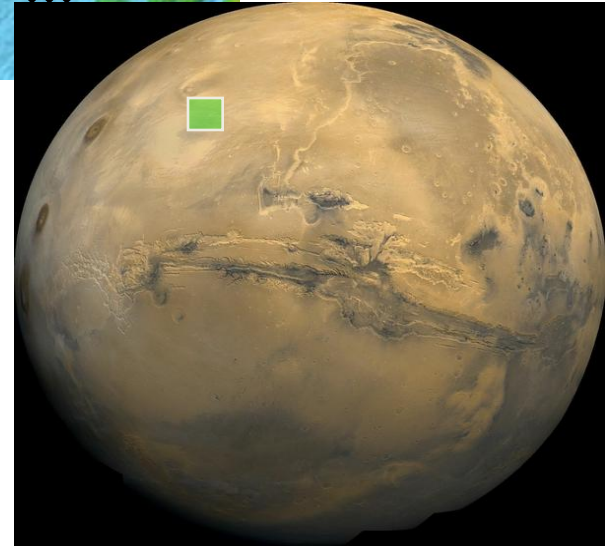
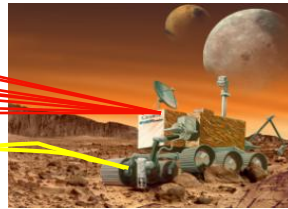
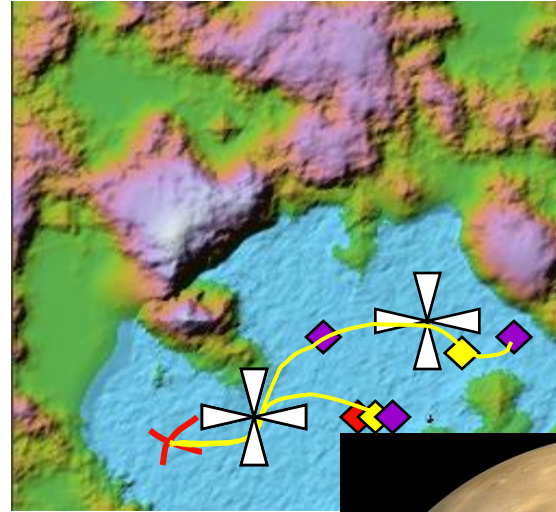


For more information visit:

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



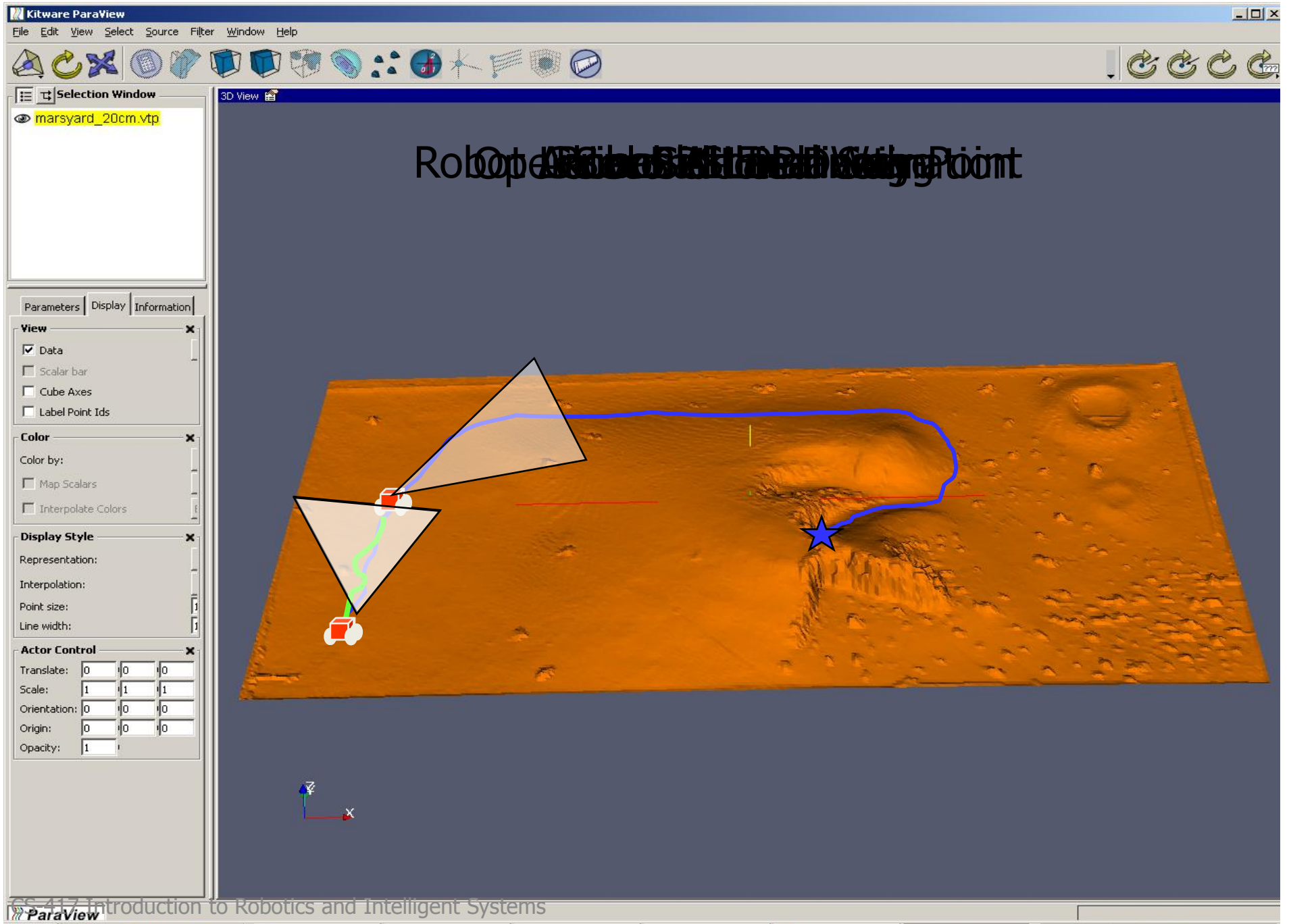
Long-Term Goal: Autonomous Robotic Exploration



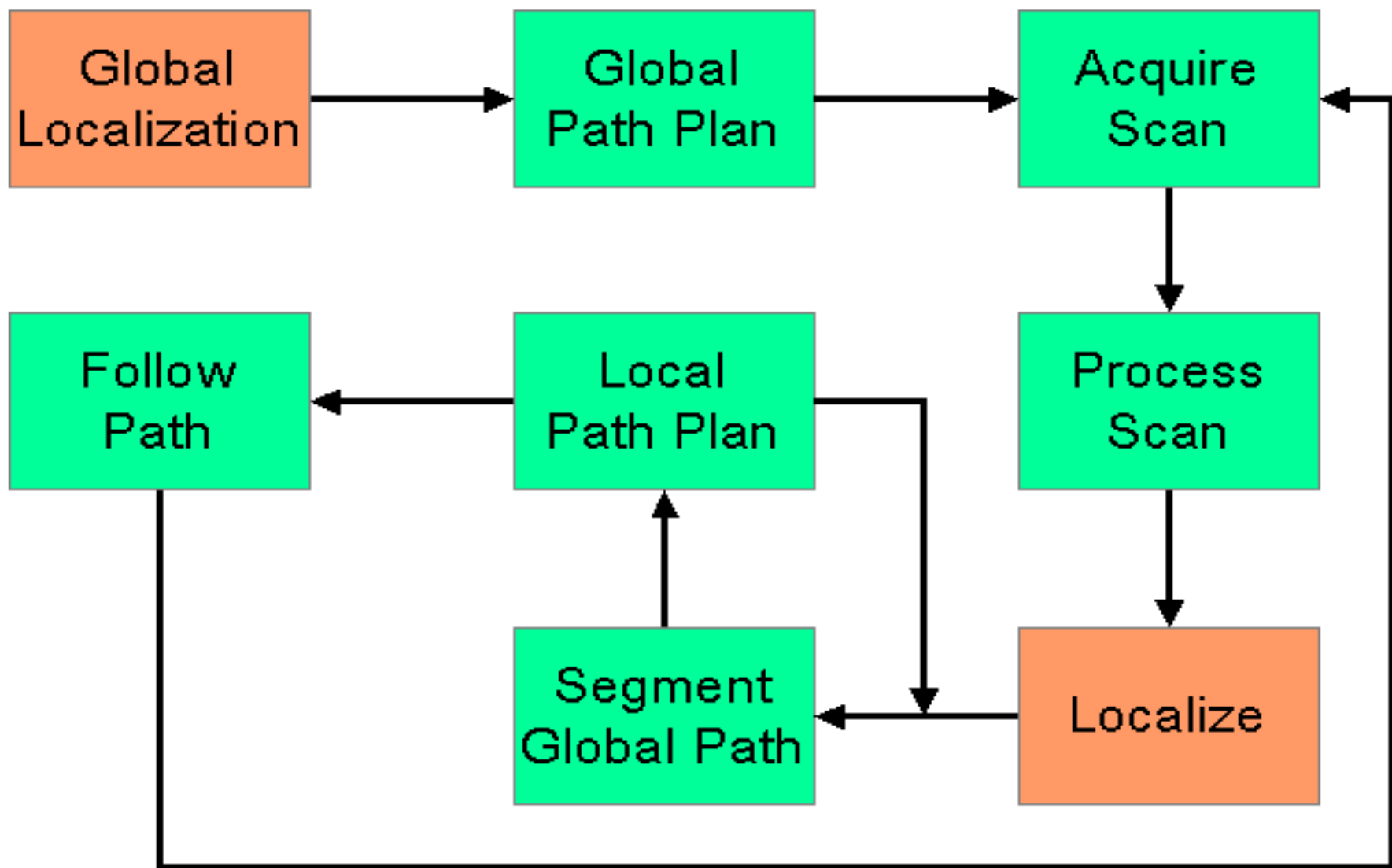
Current Research Objectives

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





Robot Position and Path

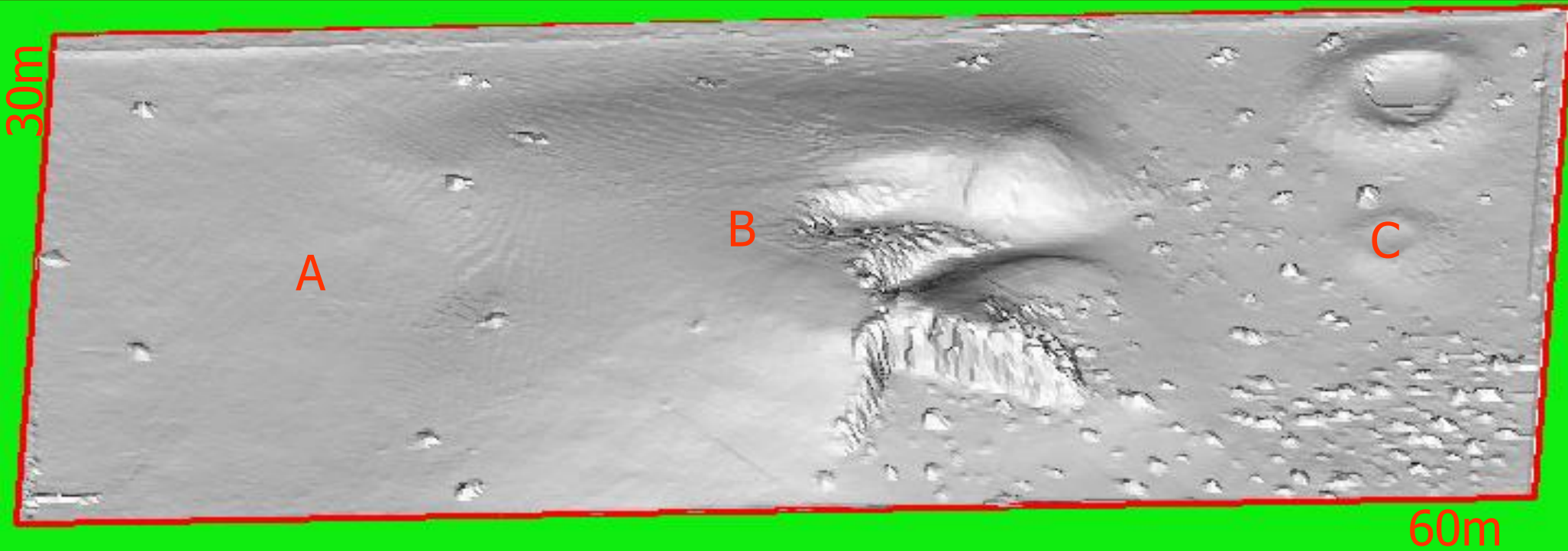


Experimental Testbed 2006

- 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

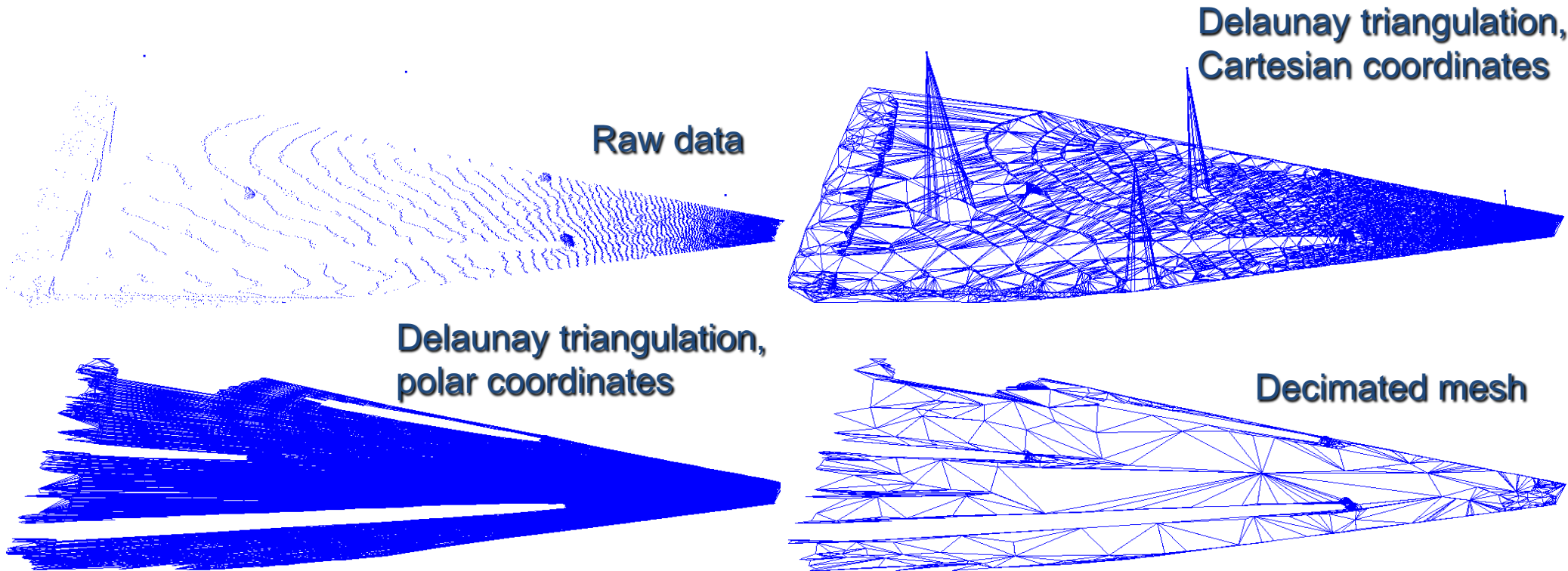


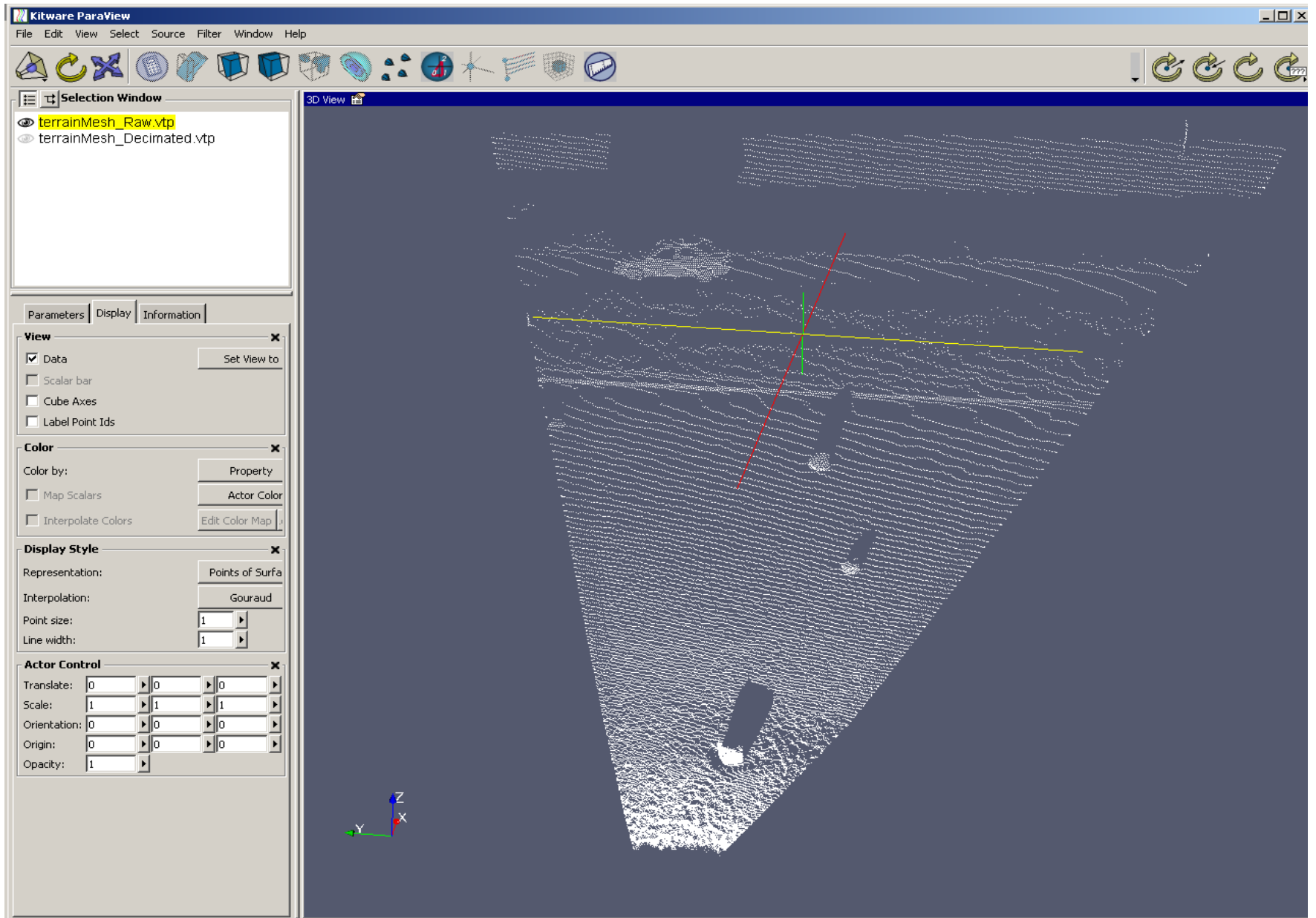
Terrain Modeling

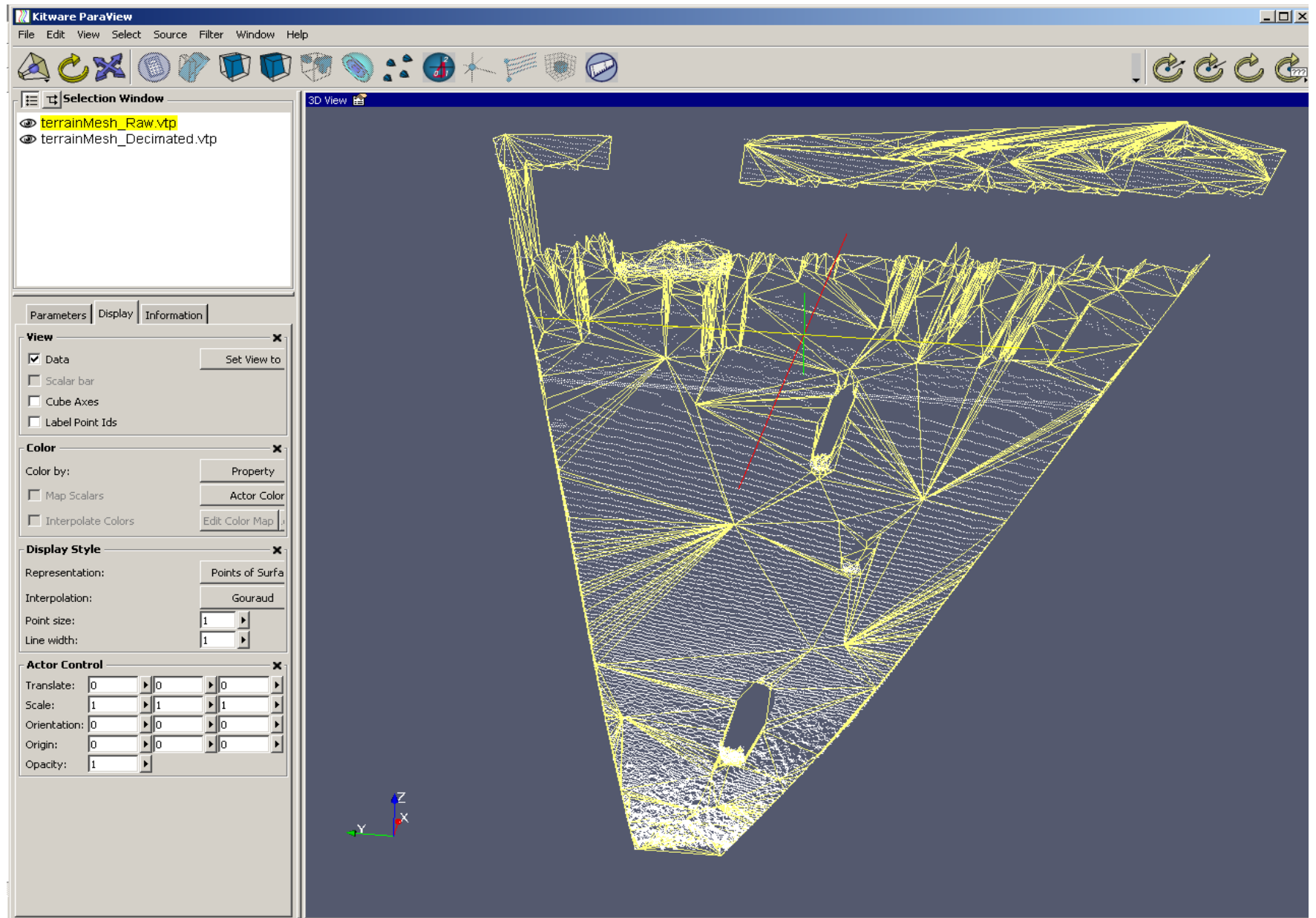
- Raw Data: 3D Point Cloud
 - Variable resolution
 - Long shadows
- Terrain Model based on Irregular Triangular Mesh (**ITM**)
 - Variable Resolution (Dense where required)
 - Memory-Efficient
 - Preserves Topography and Useful for Navigation



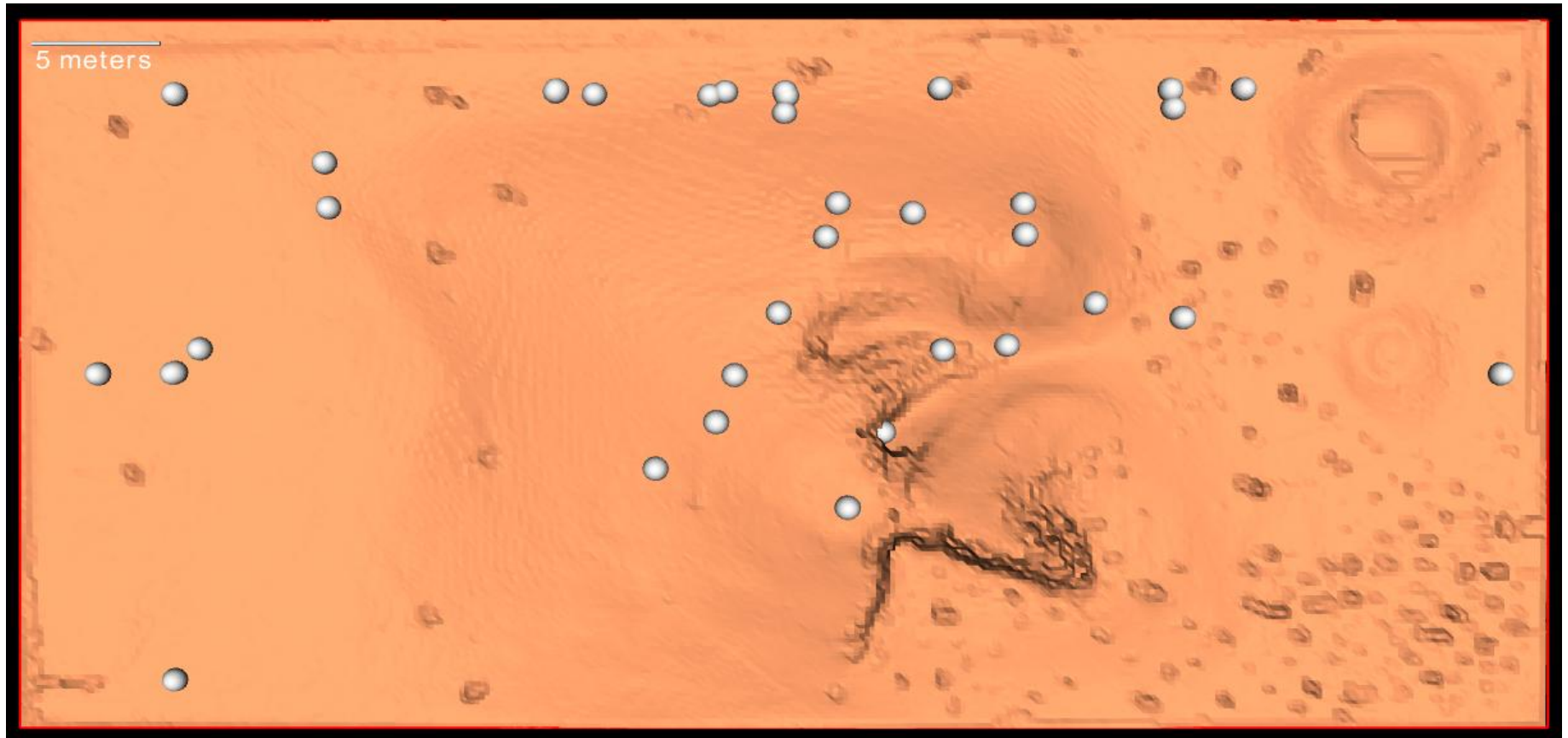
Terrain Modeling: Irregular Triangular Mesh (ITM)



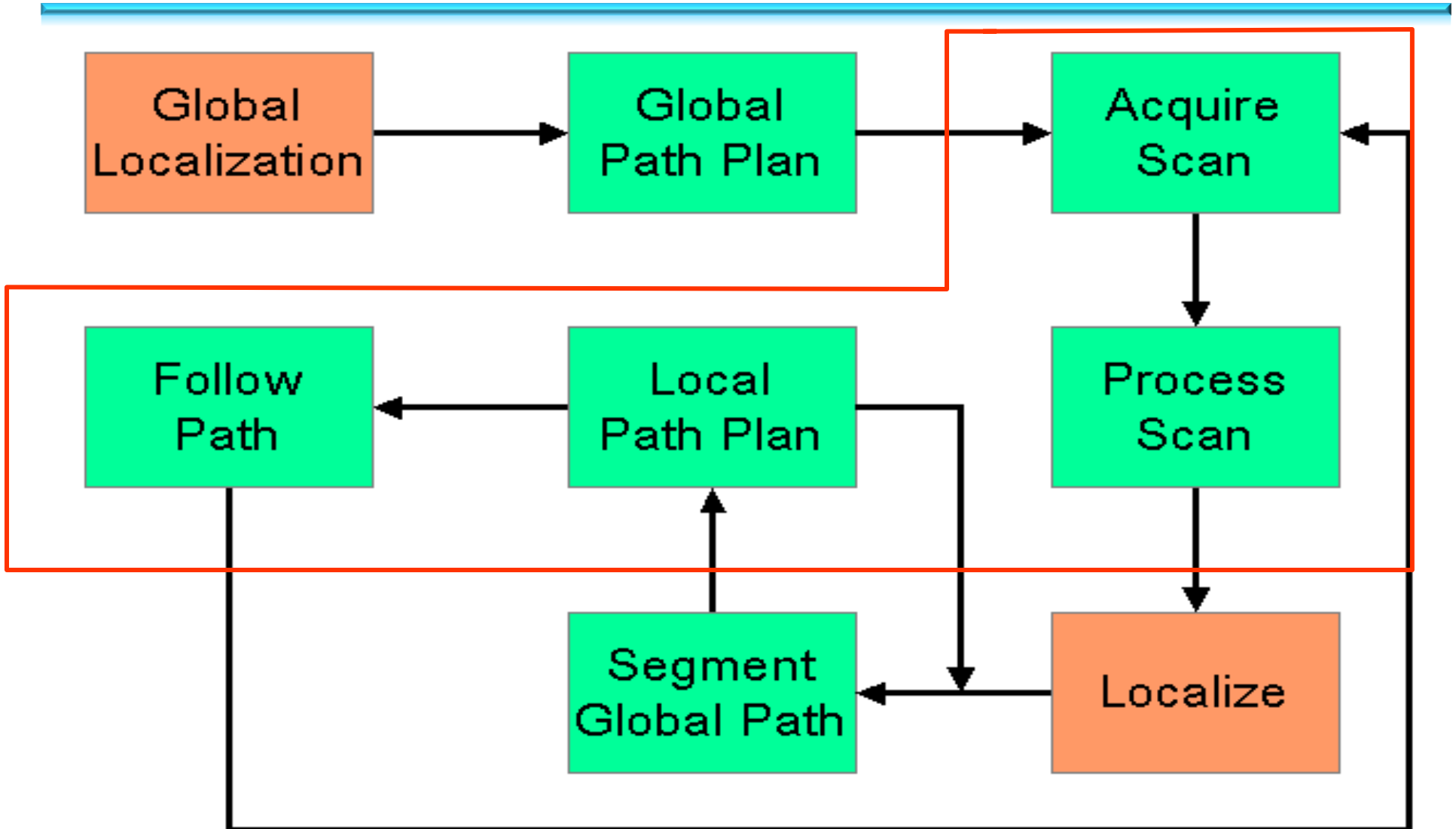




2006, Scans Collected: 96



2006, Over-the-Horizon Navigation



2006, Over-the-Horizon Traverses

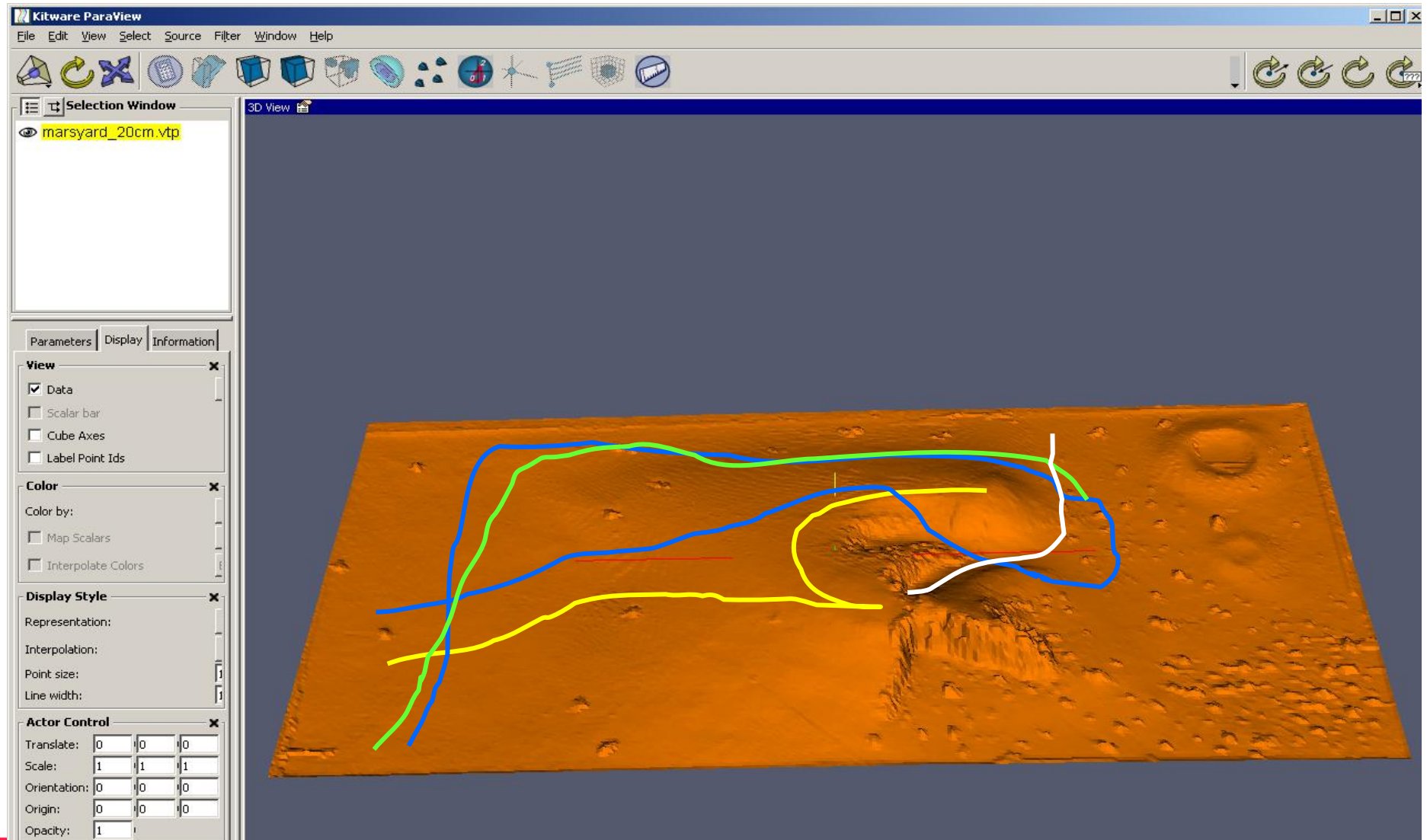
Semi-Autonomous

- 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**



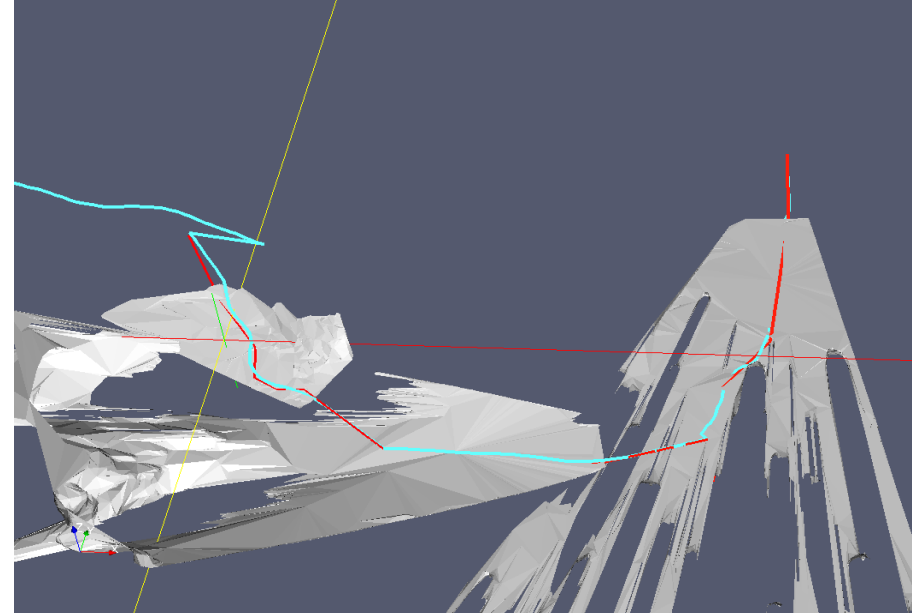
Lessons Learned

- 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



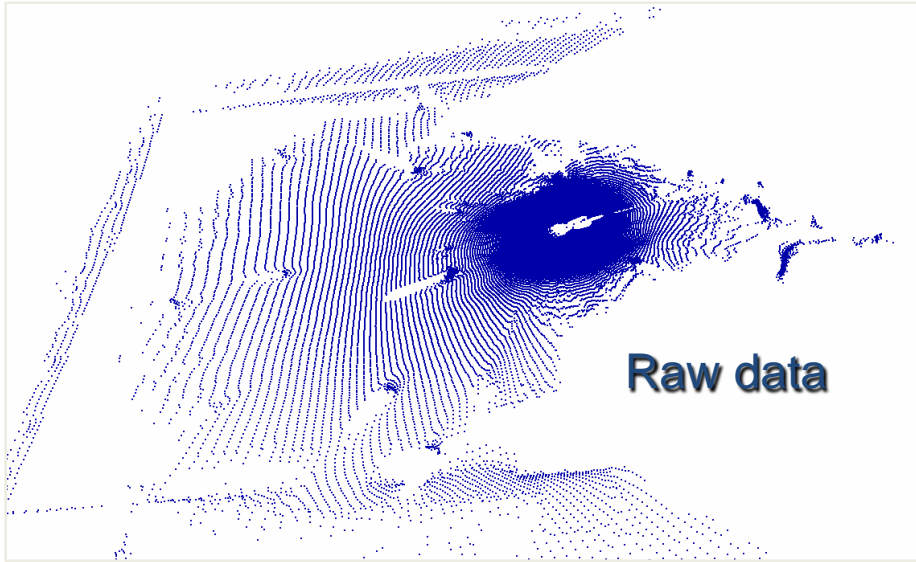
Updates in the Testbed 2007

A 360° LIDAR scanner

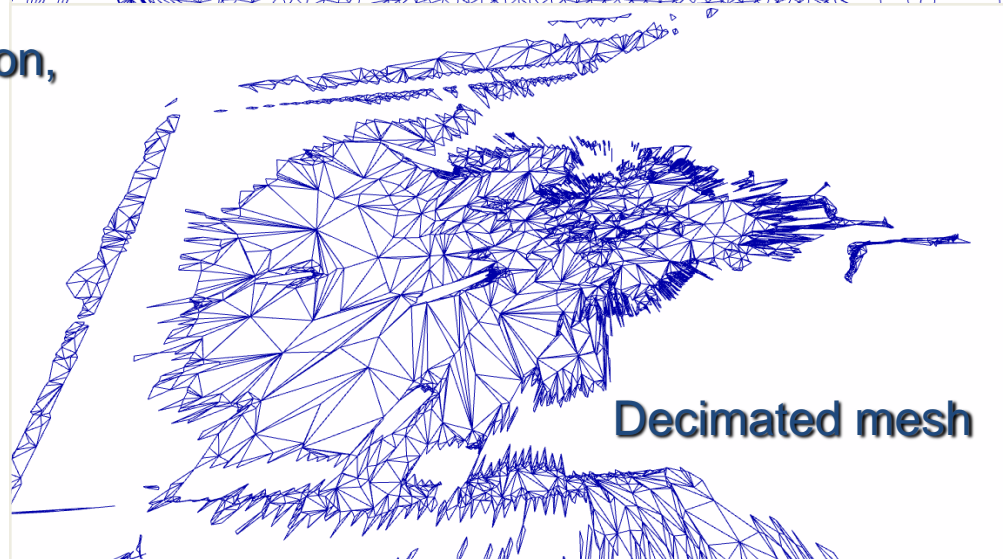
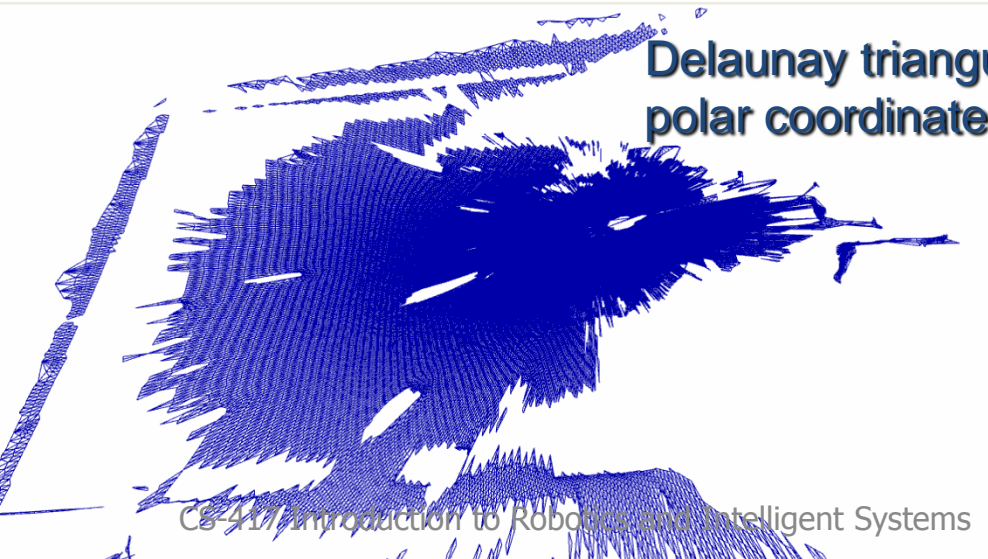
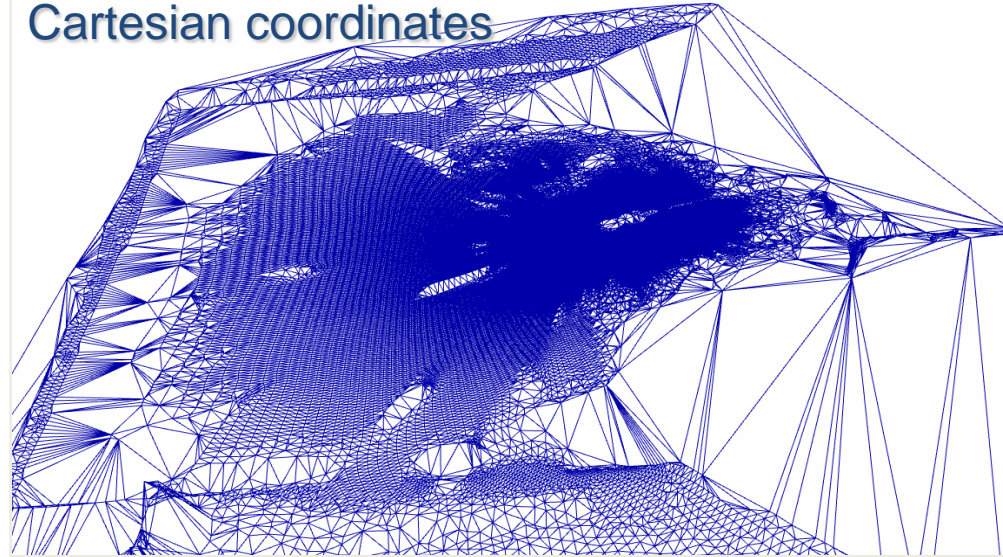
- A SICK LRF
- Mounted on a pan-unit



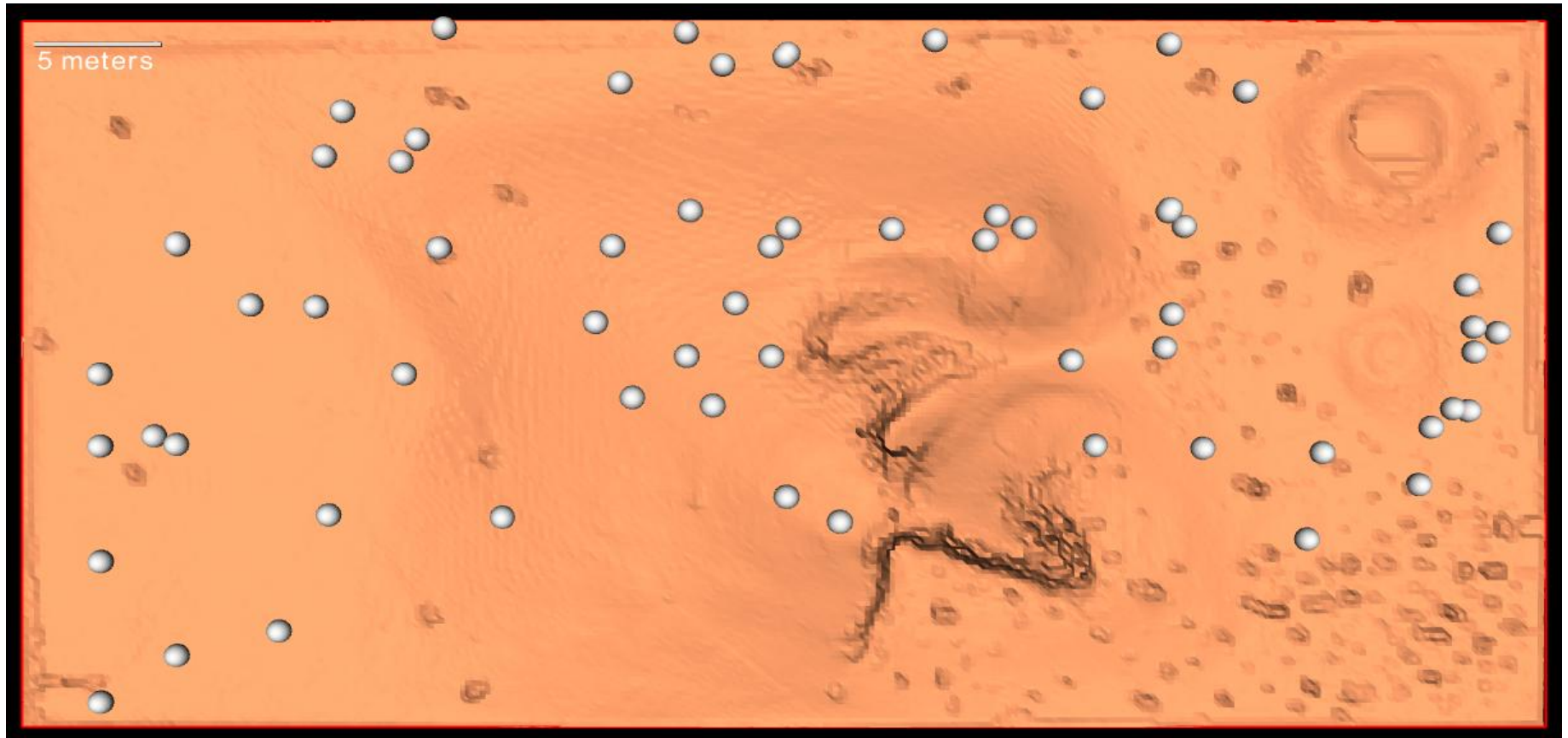
Scan Processing



Delaunay triangulation,
Cartesian coordinates



2007, Scans Collected: 93



Comparison between the two LIDARs

SICK on Pan Unit

- 360° 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**

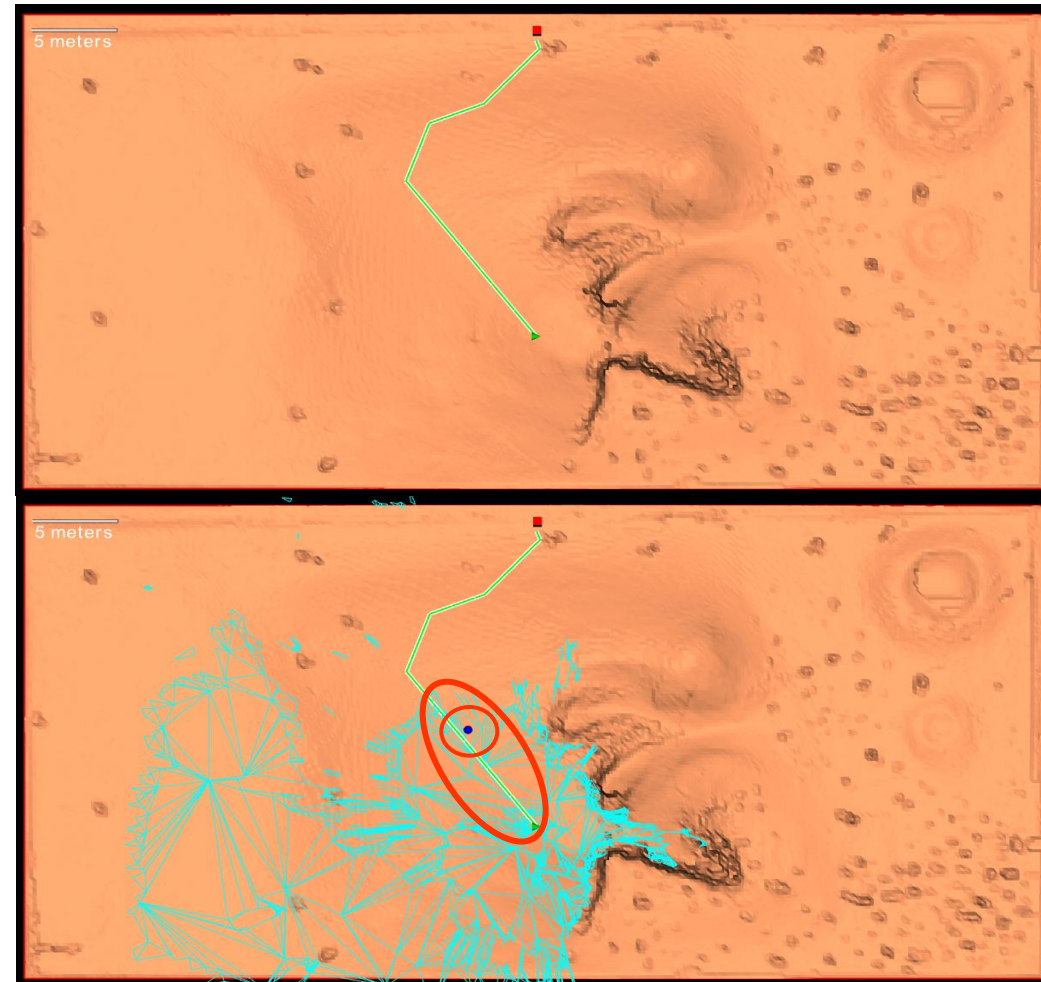
Irregular Triangular Mesh Decimation

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



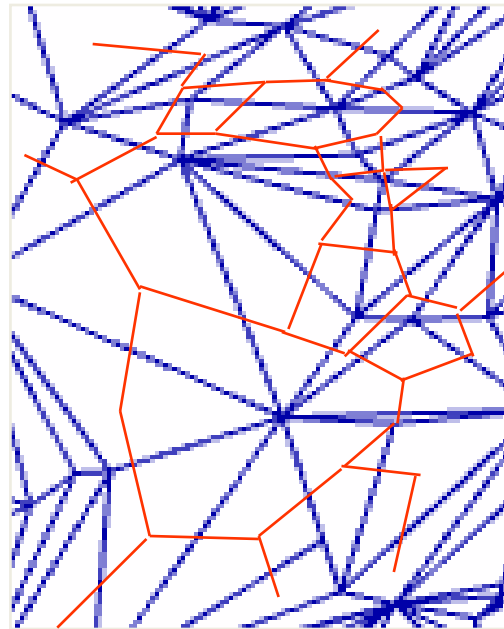
Global Path Plan and Segmentation

- 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



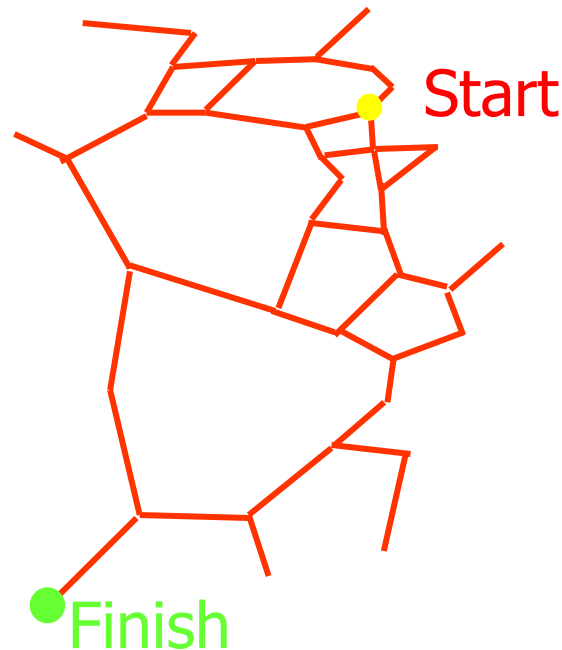
Path Planning

- Convert ITM into Connected Graph



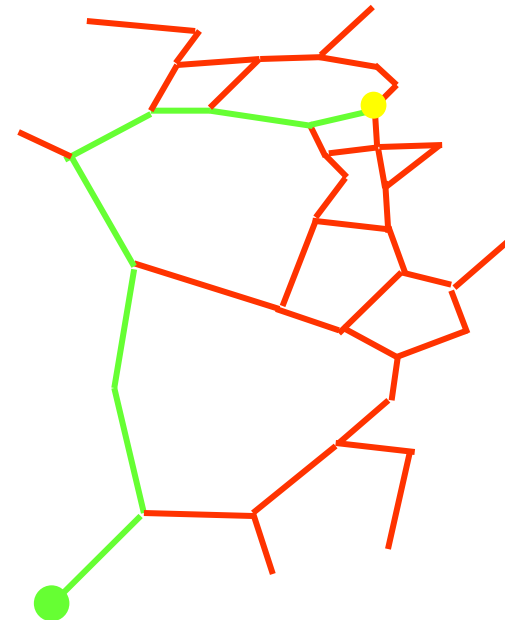
Path Planning

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



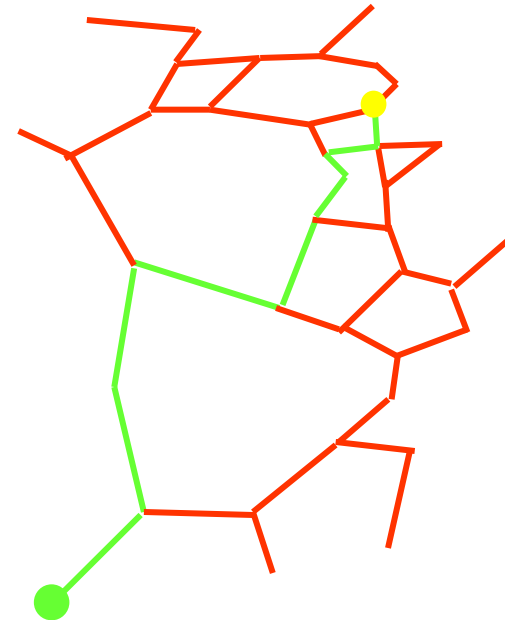
Planning

- 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

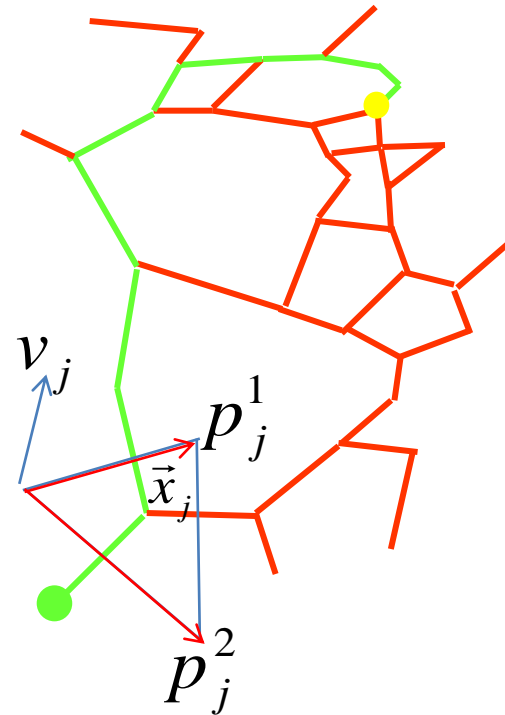
- Convert ITM into Connected Graph
- Path Planning using Graph Search Algorithms:
 - Dijkstra, A*
- Different Cost Functions Q
 - Number of triangles
 - Euclidian distance $Q = \|\vec{x}_i - \vec{x}_j\|$



Planning

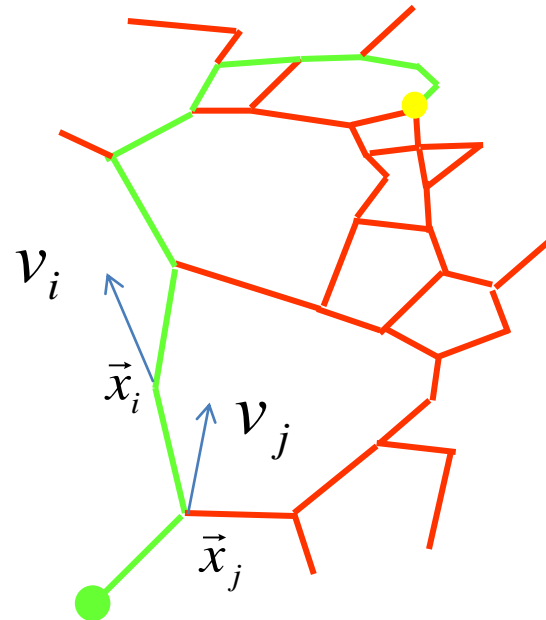
- Convert ITM into Connected Graph
- Path Planning using Graph Search Algorithms:
 - Dijkstra, A*
- Different Cost Functions Q
 - Number of triangles
 - Euclidian distance
 - Slope of each triangle

$$v_j = \frac{p_j^1 \times p_j^2}{\|p_j^1\| \|p_j^2\|}$$



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

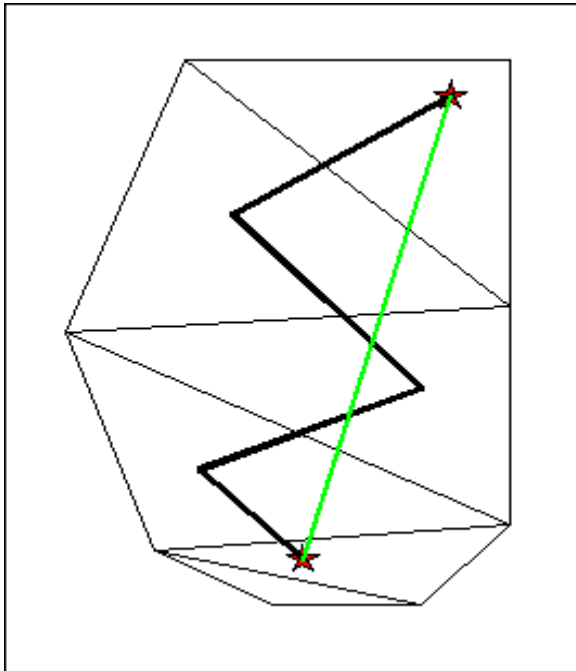
- Convert ITM into Connected Graph
- Path Planning using Graph Search Algorithms:
 - Dijkstra, A*
- Cost function:
 - Distance travelled
 - Penalty for uphill slope
 - Infinite cost for moving into too-steep triangles
 - Roughness of the area under the footprint of the robot
 - A* is biasing the cost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



Path Simplification

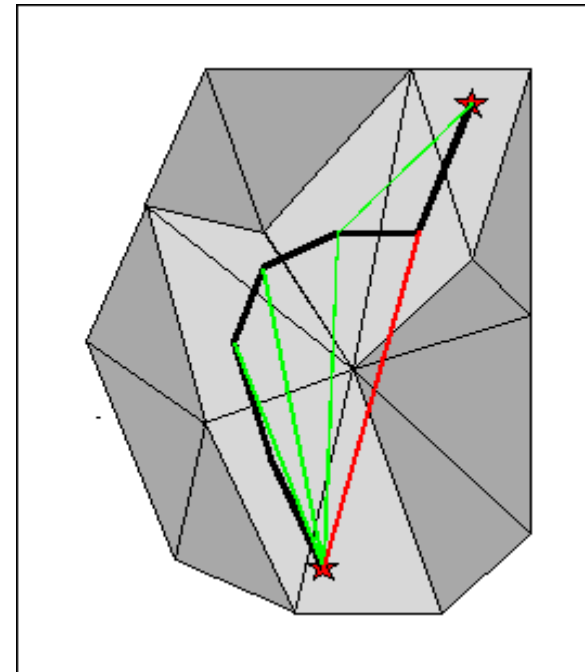
- Path Simplification

Point-Robot

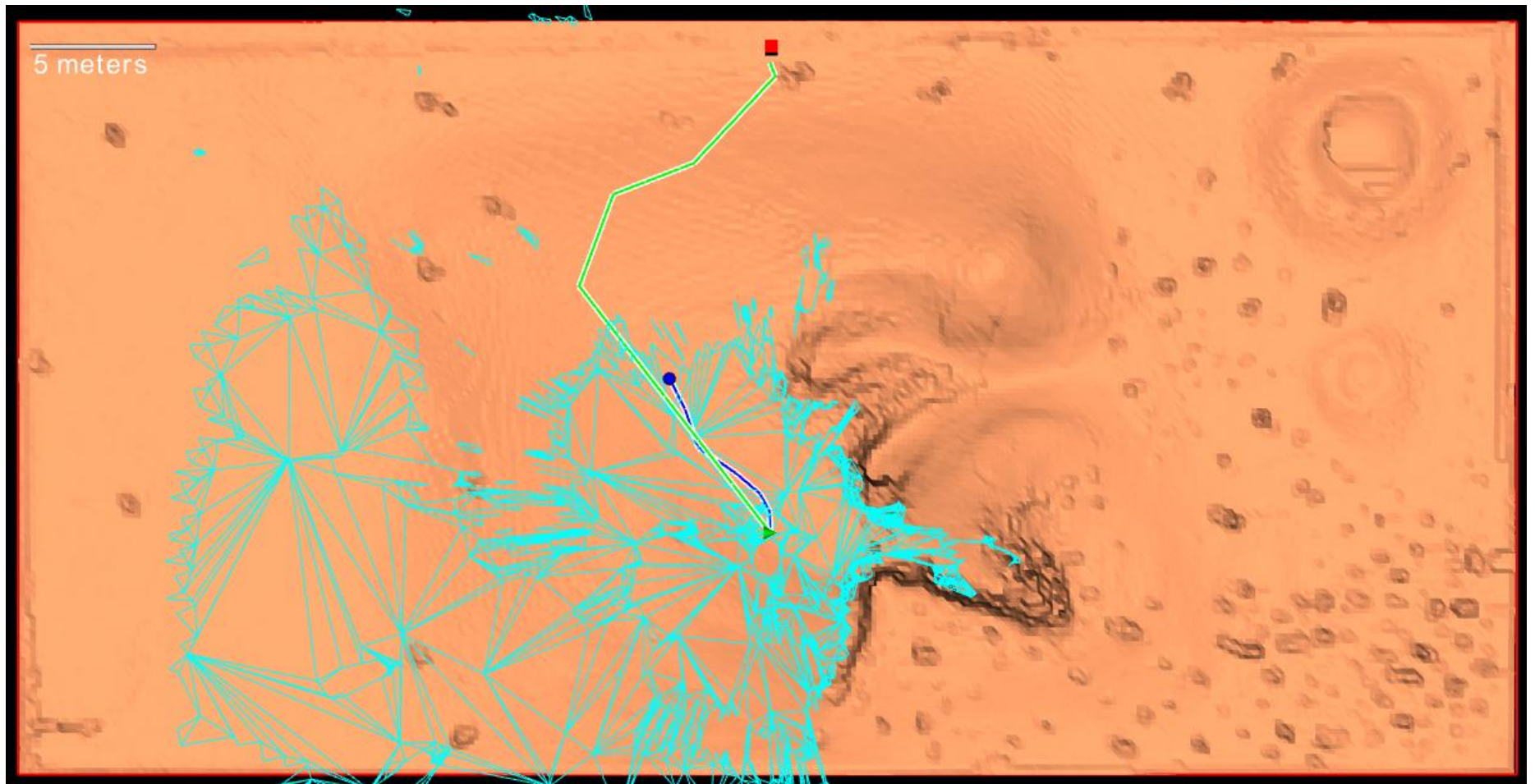


- Path Simplification

Safety Corridor



Local Path Plan

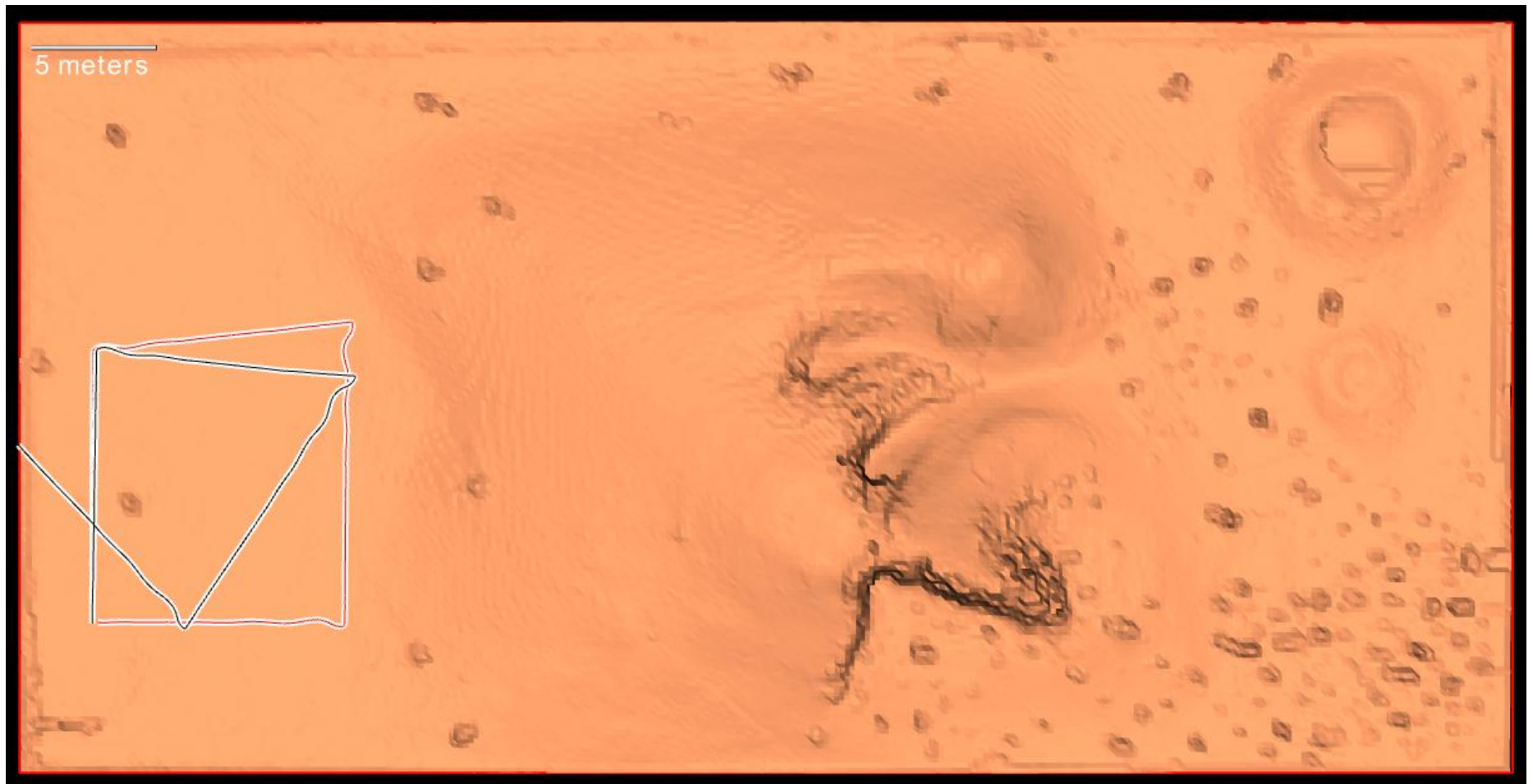


Motion Control

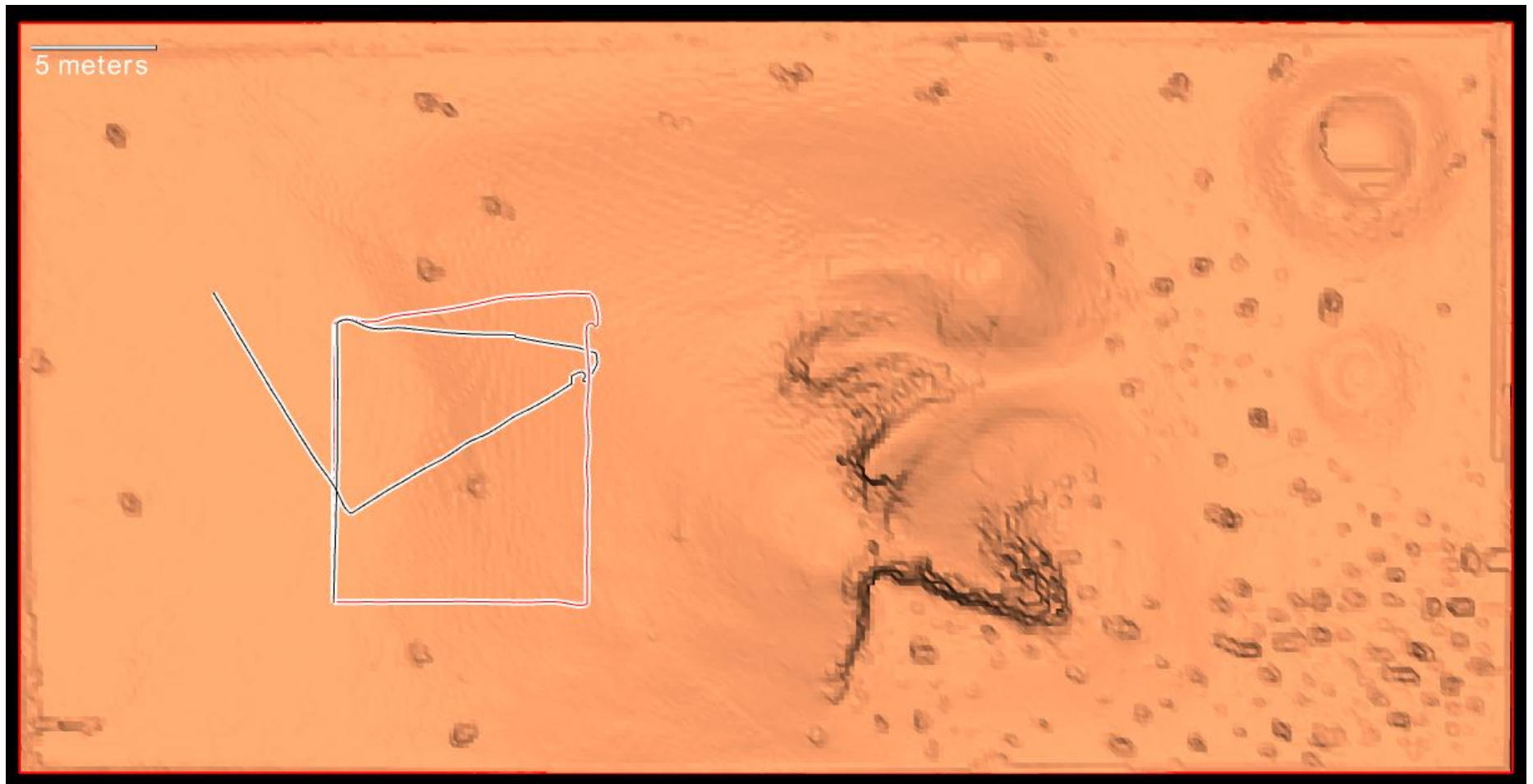
- Sensor Suite: Wheel Odometry, IMU, Heading sensor, No Visual Odometry
- 3D Pose Estimation:
 - Filter combines IMU+Odometry
 - No uncertainty estimation (currently)
- Path approximated with Catmull-Rom spline for smoothness
- Astolfi controller follows the spline trajectory



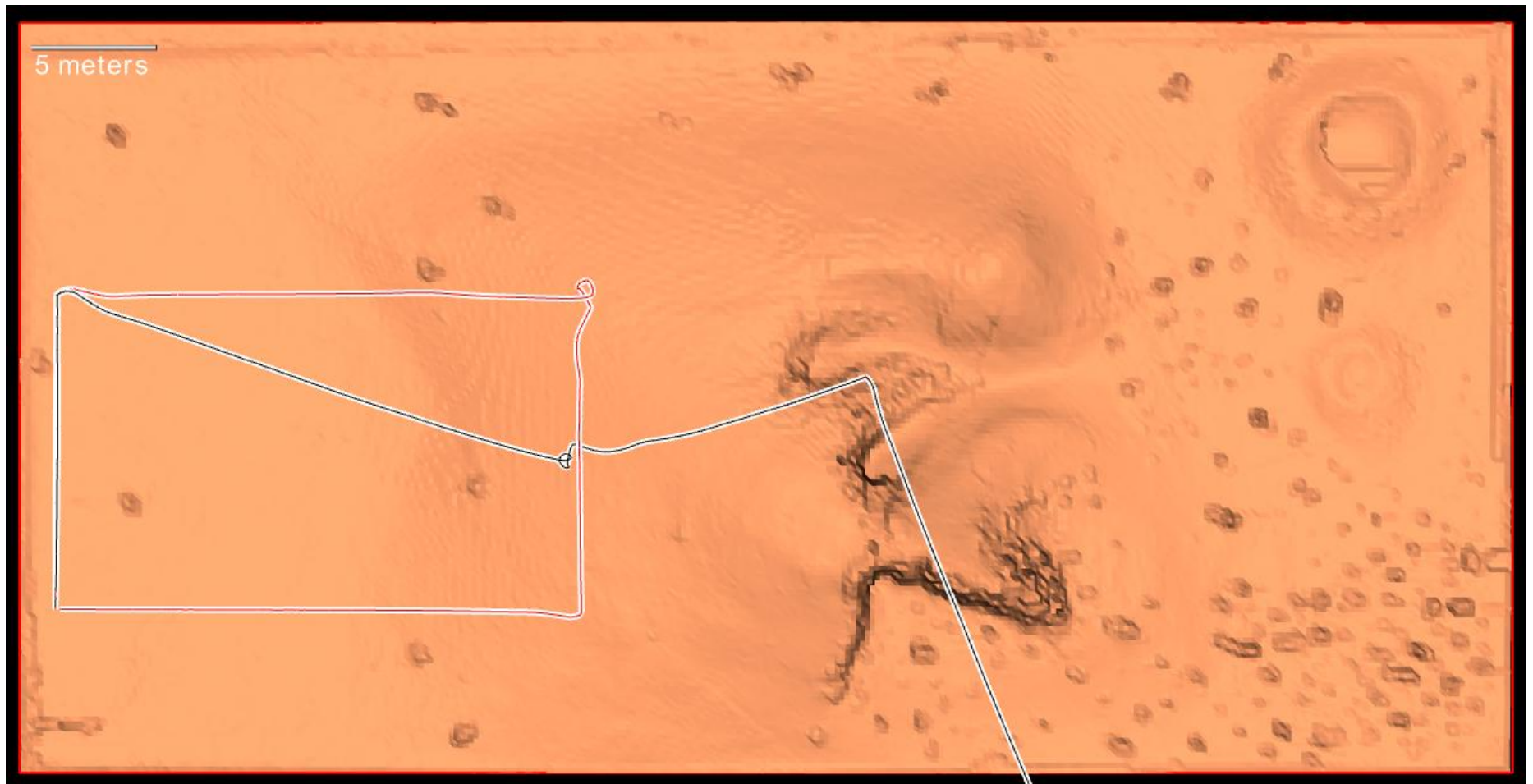
Closed Loop Tests



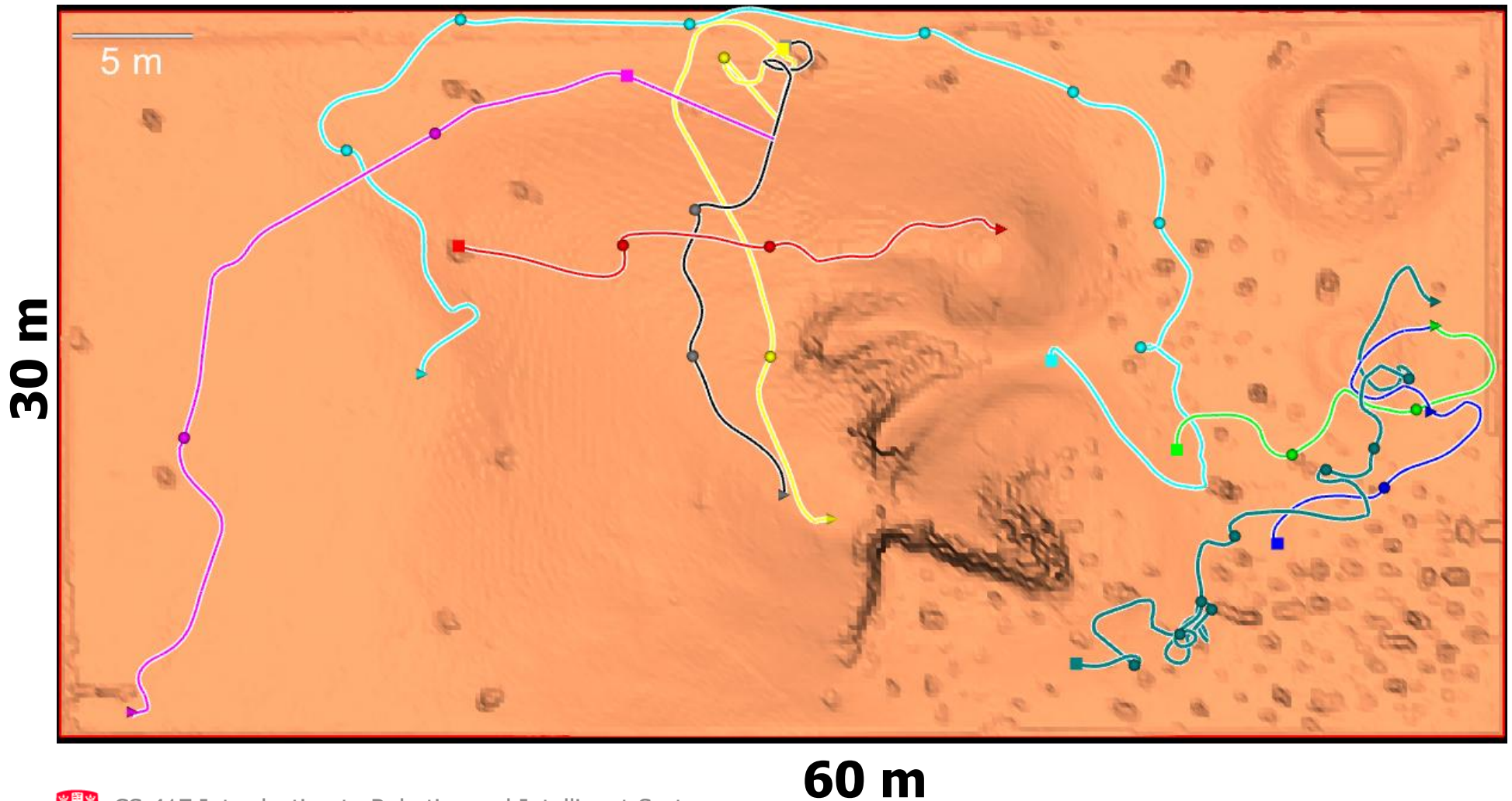
Closed Loop Tests



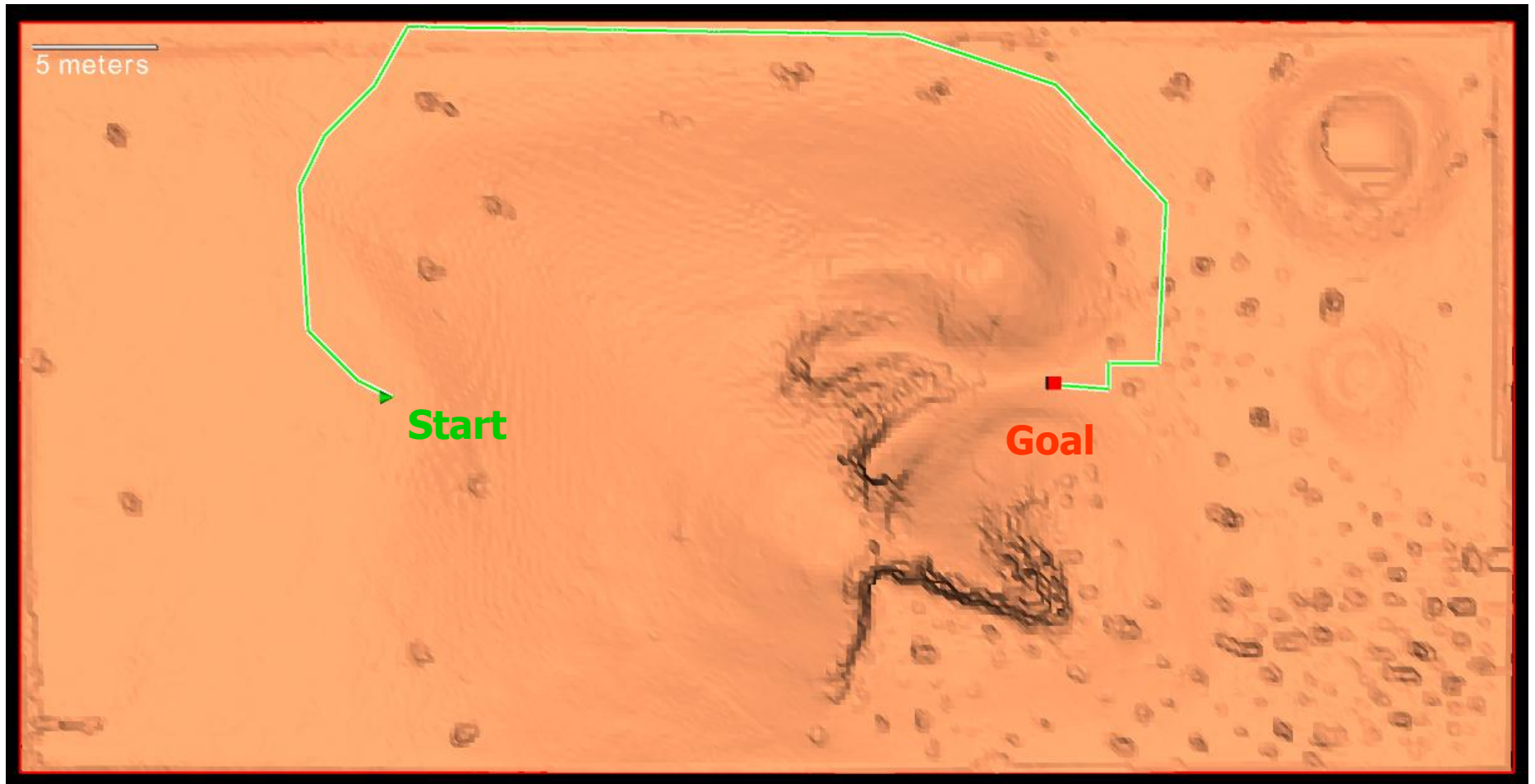
Closed Loop Tests



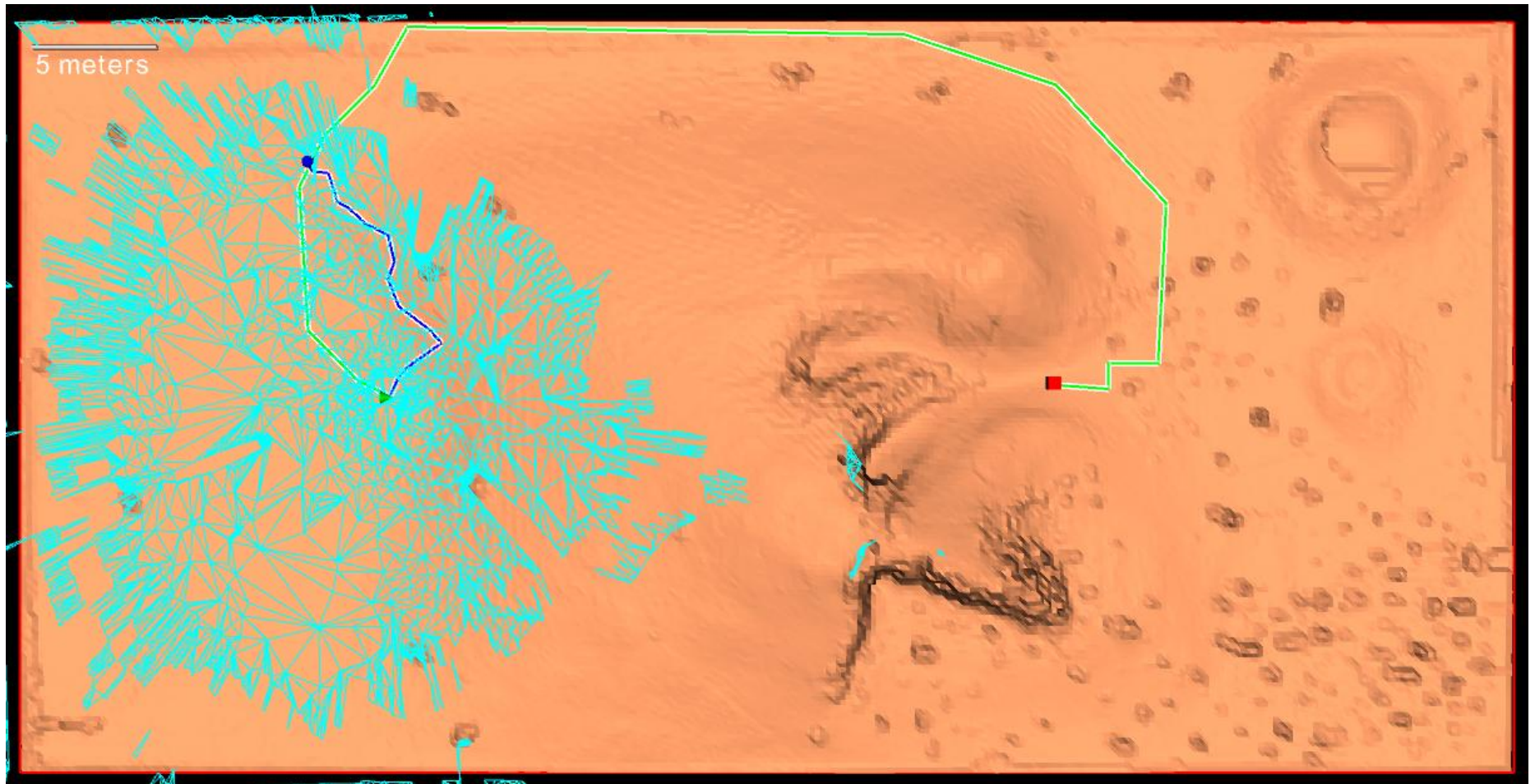
The Mars Terrain and Trajectories



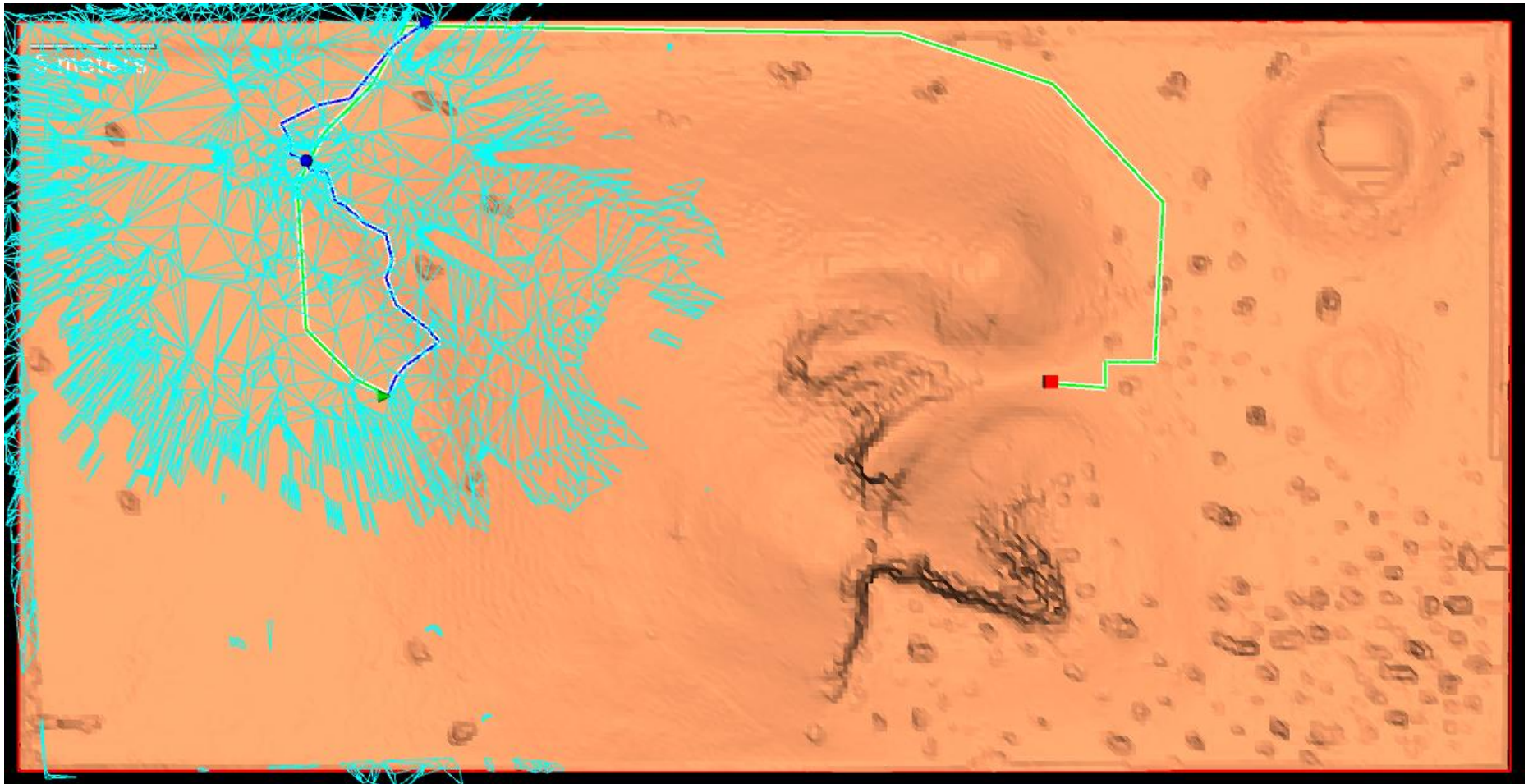
Fully Autonomous Navigation from flat to canyon



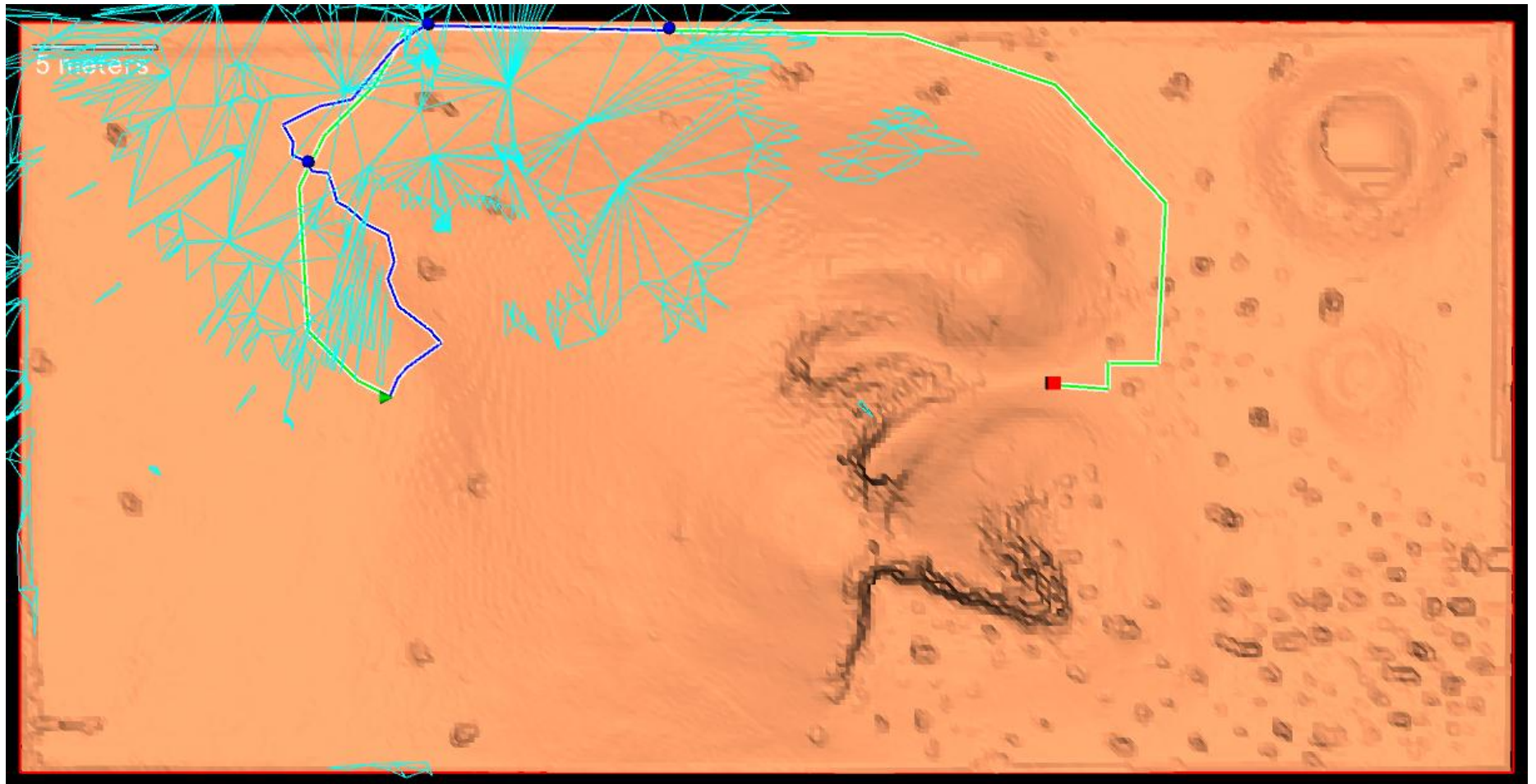
Fully Autonomous Navigation from flat to canyon



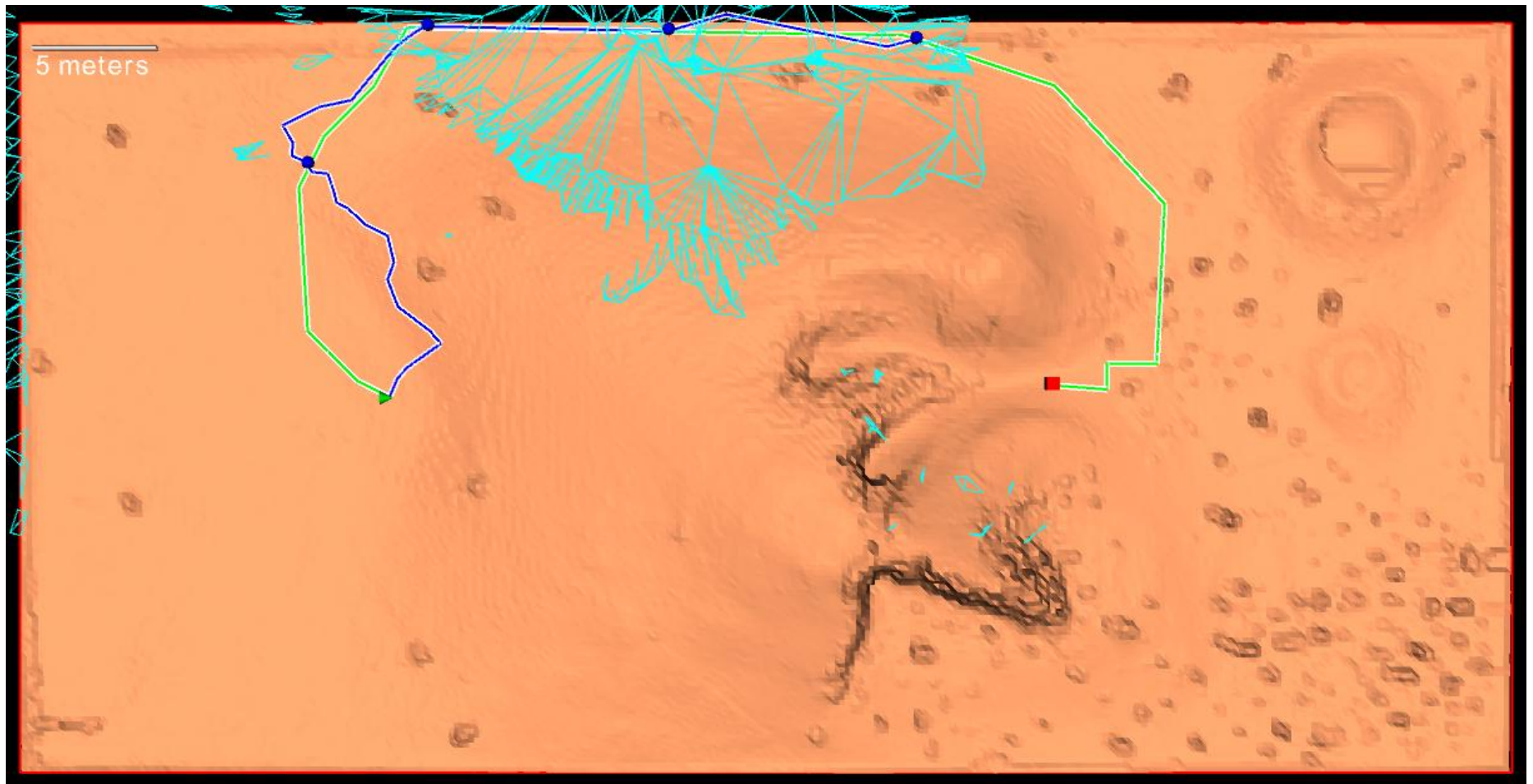
Fully Autonomous Navigation from flat to canyon



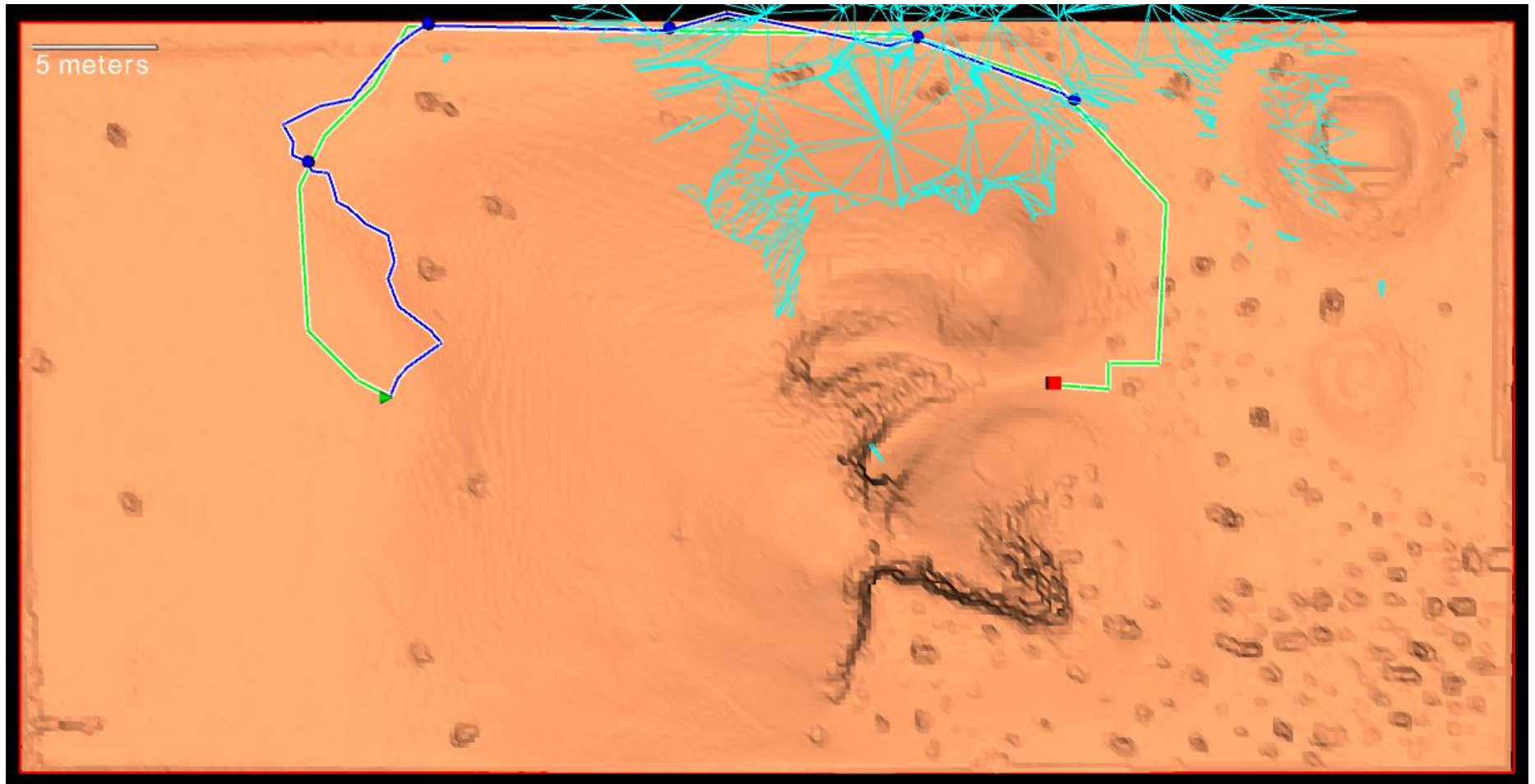
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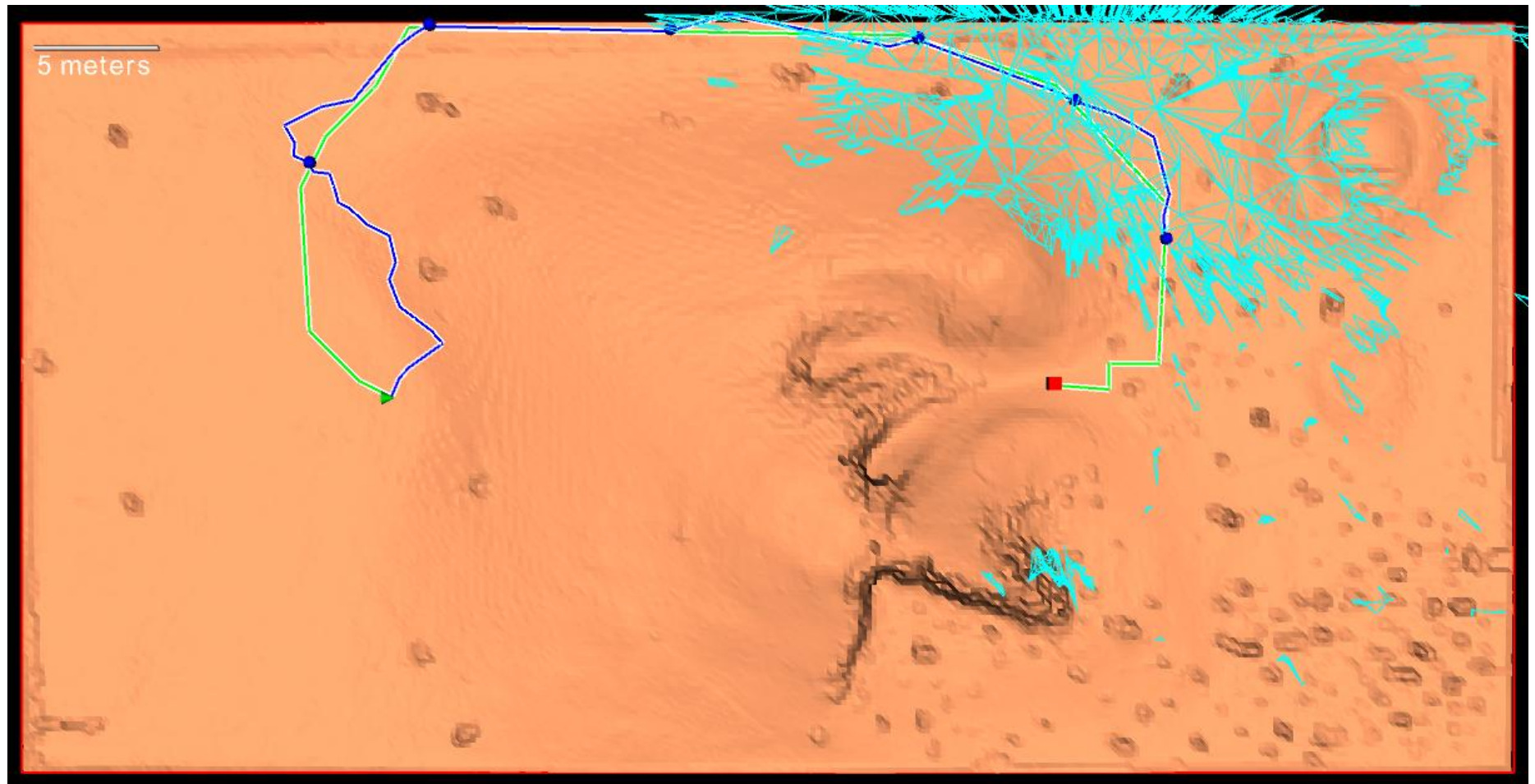
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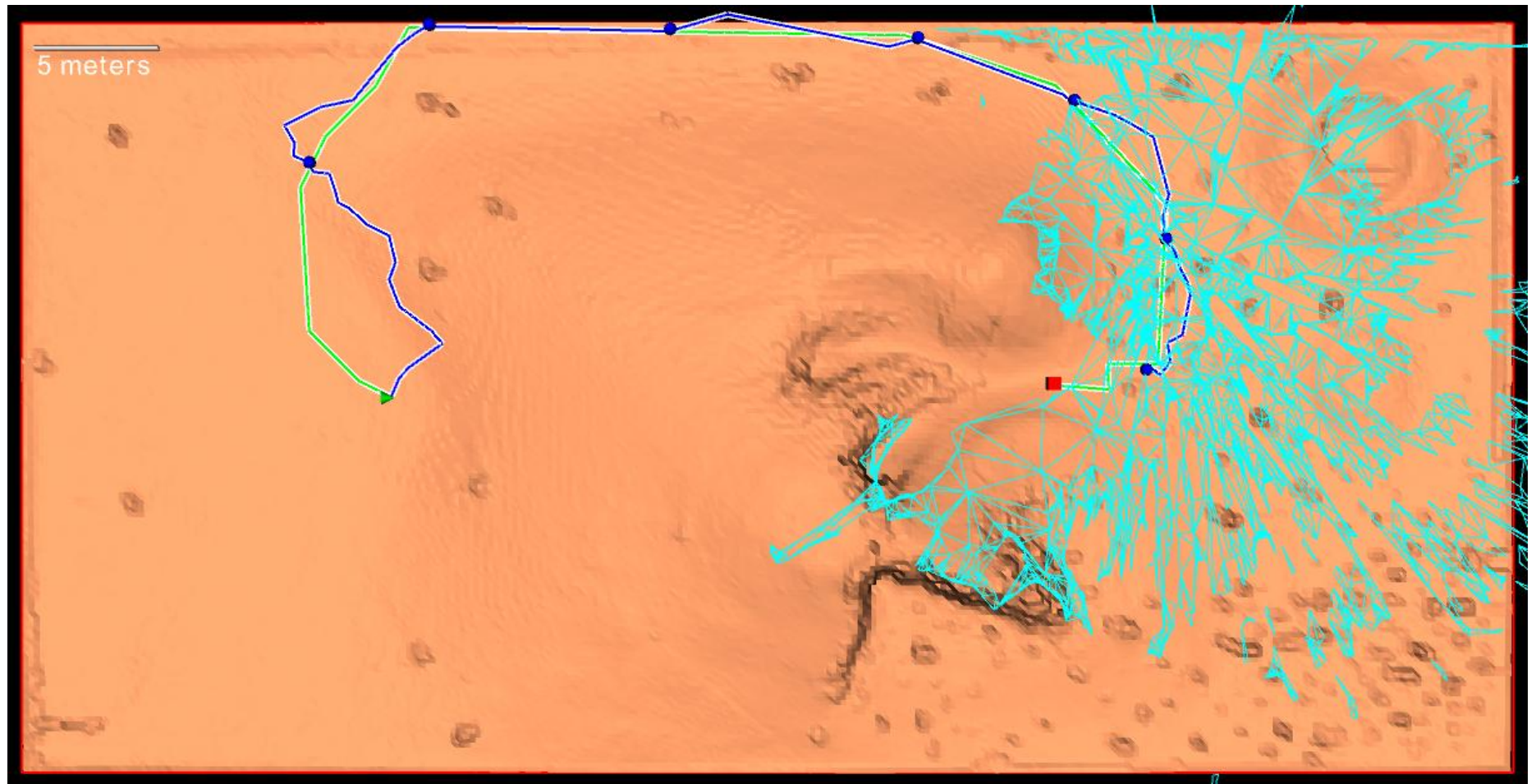
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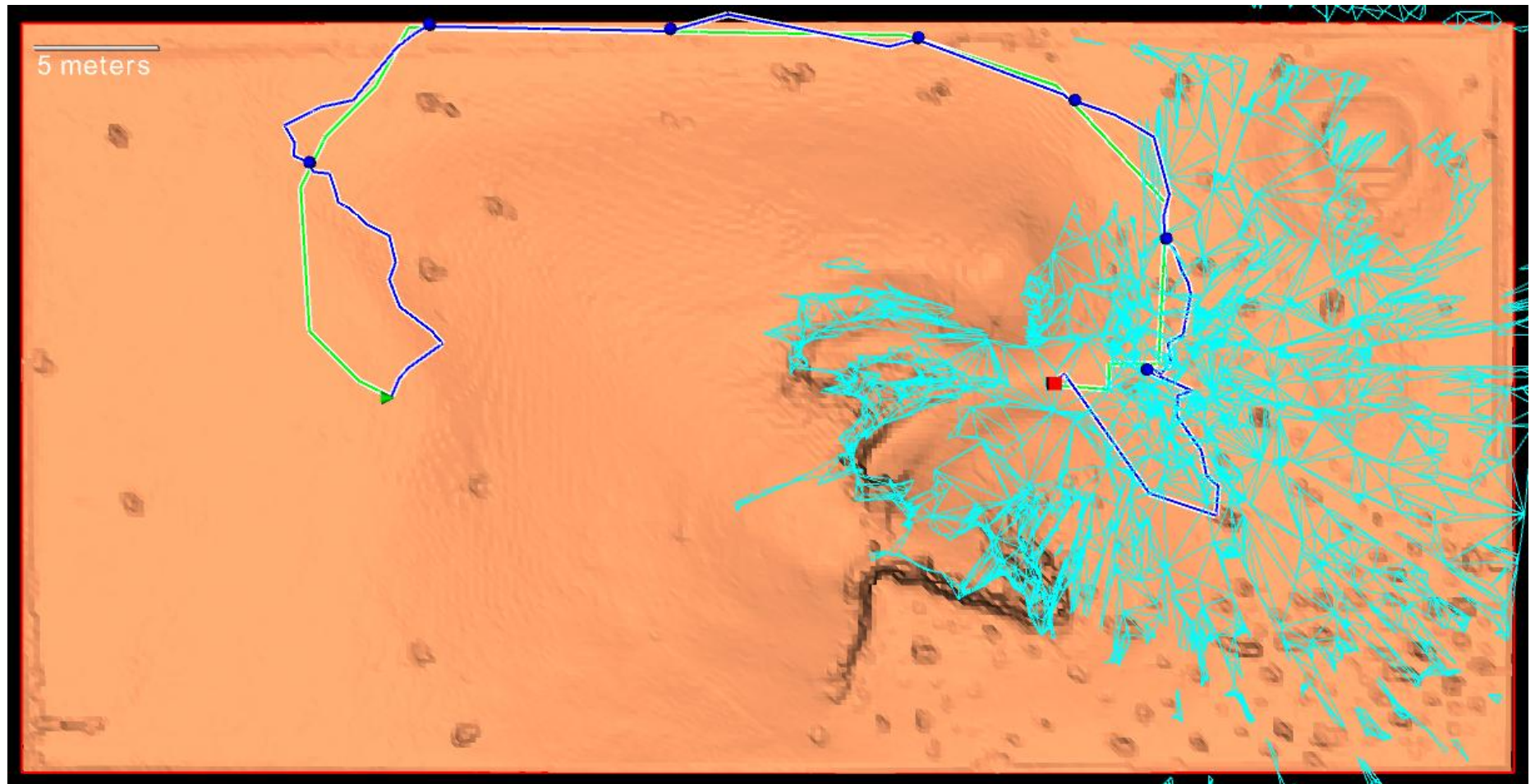
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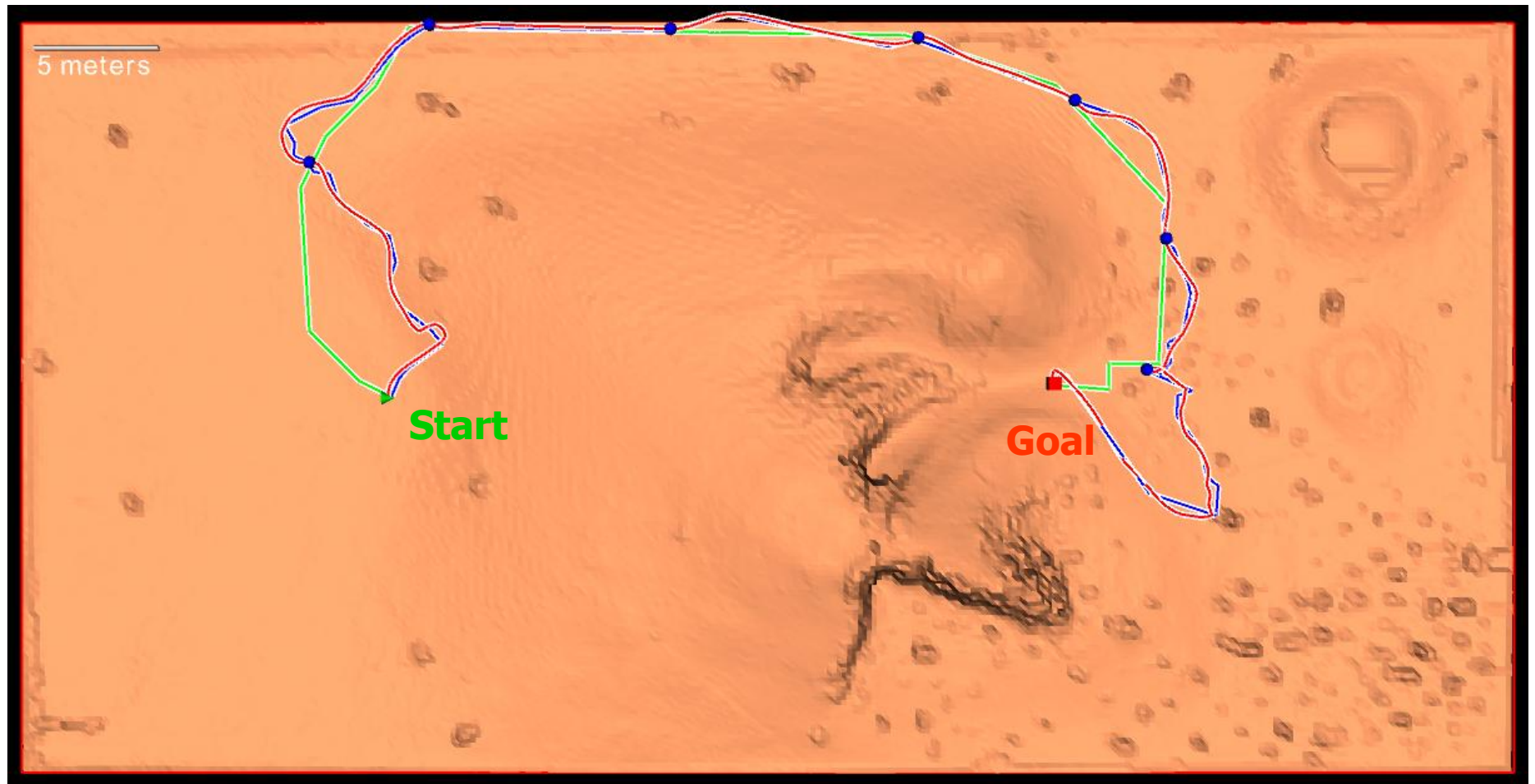
Fully Autonomous Navigation from flat to canyon



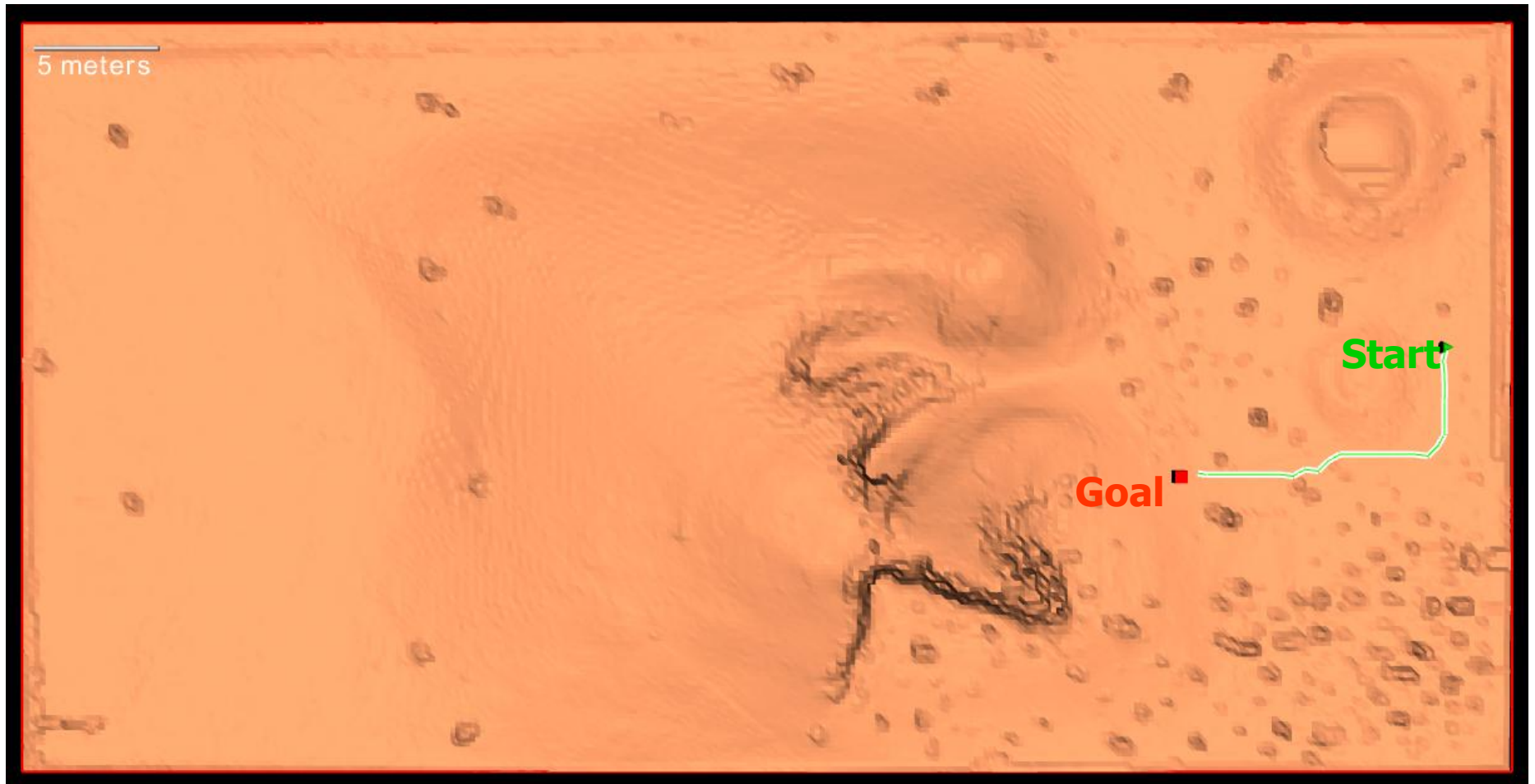
Fully Autonomous Navigation from flat to canyon



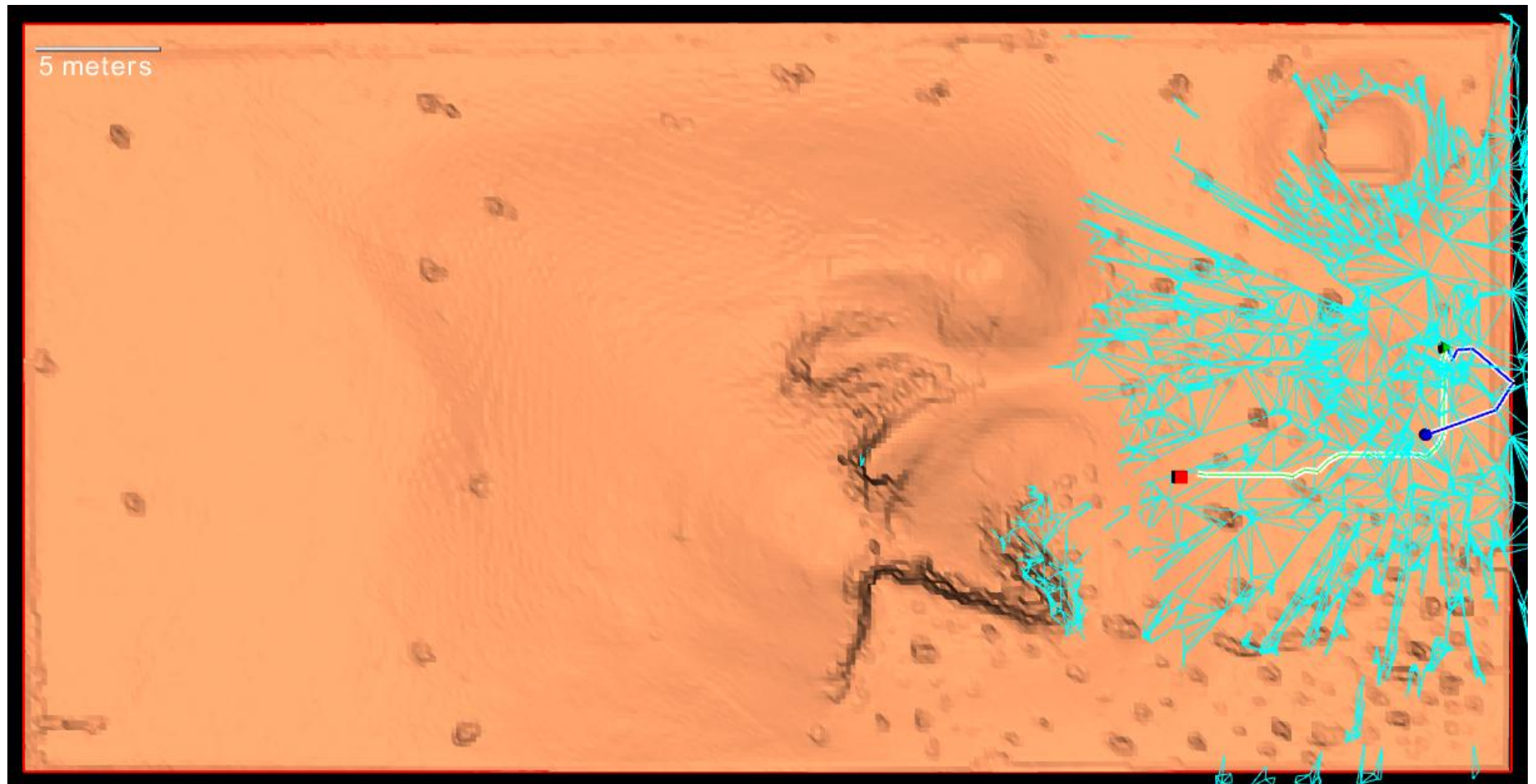
Fully Autonomous Navigation from flat to canyon



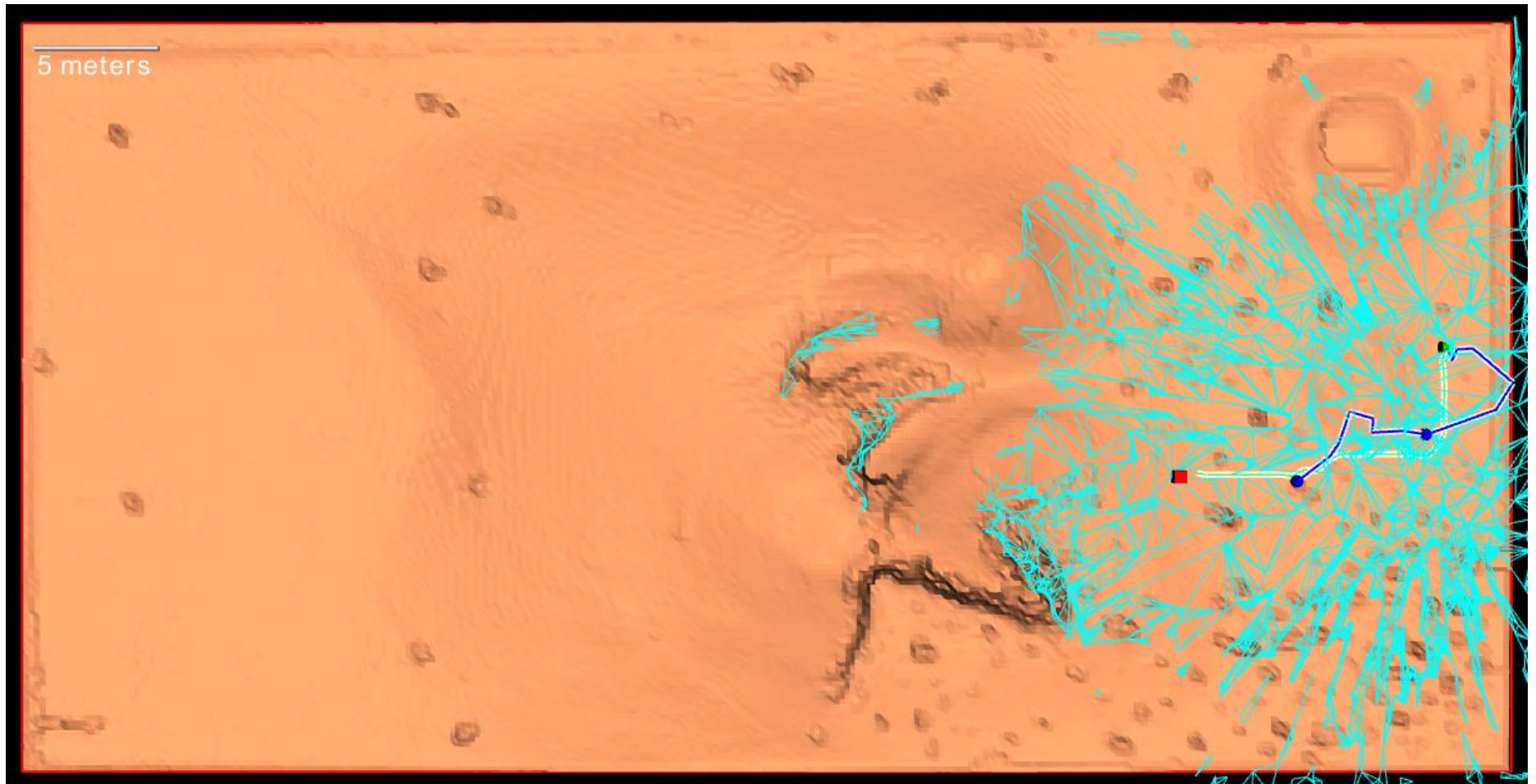
Fully Autonomous Navigation from crater to canyon



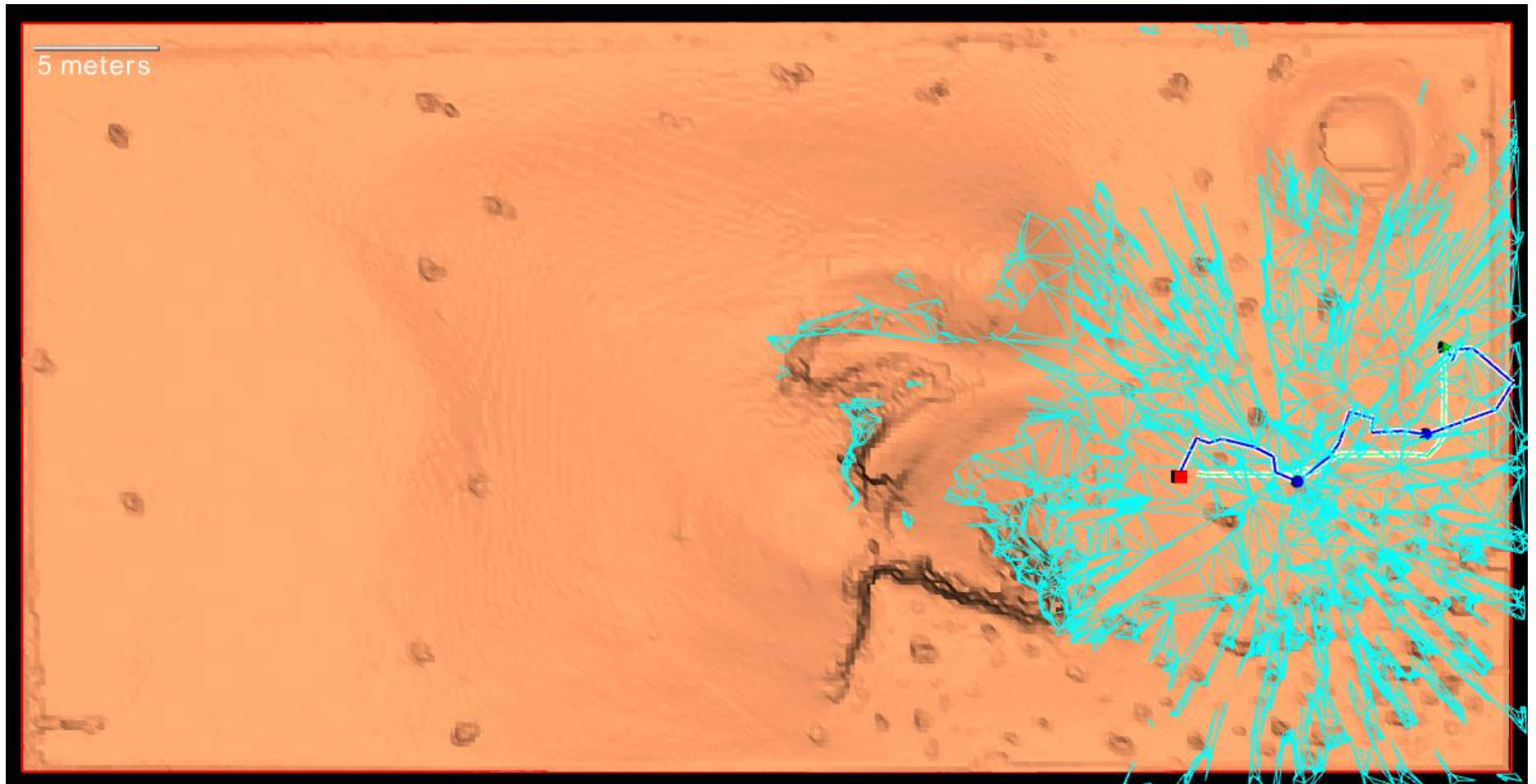
Fully Autonomous Navigation from crater to canyon



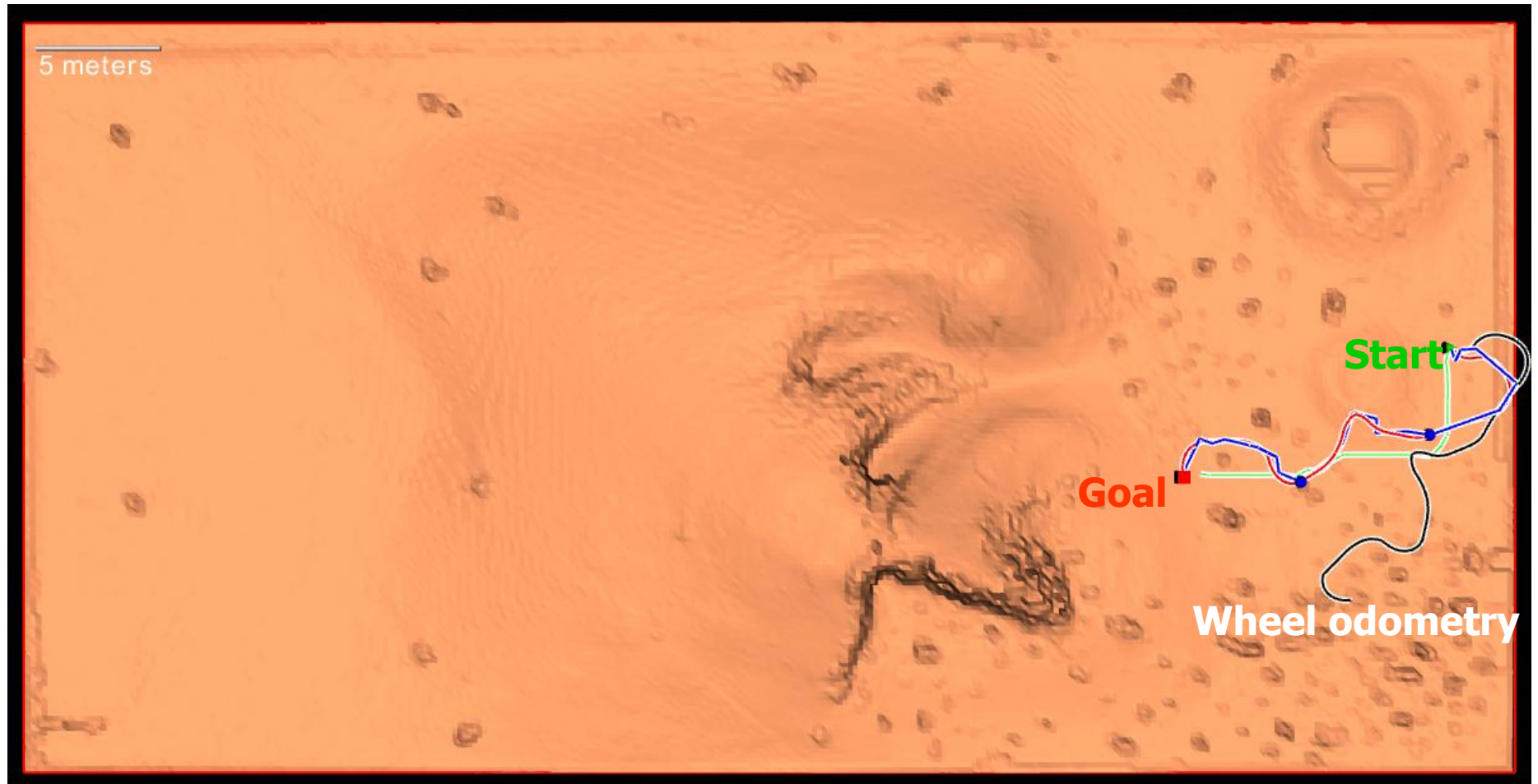
Fully Autonomous Navigation from crater to canyon



Fully Autonomous Navigation from crater to canyon



Fully Autonomous Navigation from crater to canyon



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 see?
 - 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)

