CS-417 INTRODUCTION TO ROBOTICS AND INTELLIGENT SYSTEMS

Space Robotics

Ioannis Rekleitis

Why Space Robotics

- “Final Frontier” – “To boldly go where no robot has gone before”
- Dangerous, Tedious Work
- High scientific return on investment
- Canadian presence strong
  - Canadarm
  - Canadarm2
  - Shuttle inspection laser and boom
  - Participation in many other missions

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, Kourosh Parsa, and Erick Dupuis

Space Technologies
Canadian Space Agency
Montréal, Canada

Presented at the 2006 International Conference on Robotics and Automation

Motivation

- More than 19K objects bigger than 10cm in orbit (2009)
- Between 1-10cm 500K (2009)
- 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

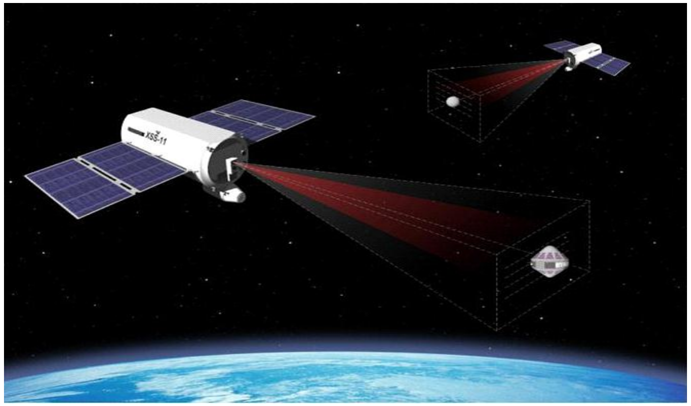
SOLUTION

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

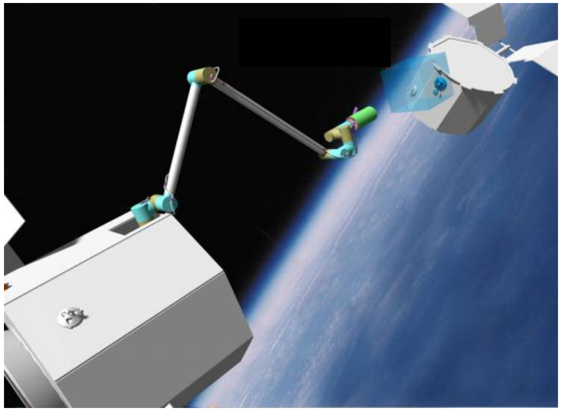
On-Orbit Servicing Opportunities

- OOS missions with Canadian involvement

Shuttle Return to Flight

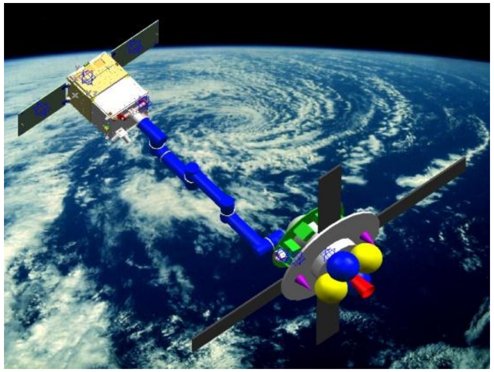


XSS-11



Orbital Express

Hubble servicing study



TECSAS

MBS, Canadarm2, Dextre

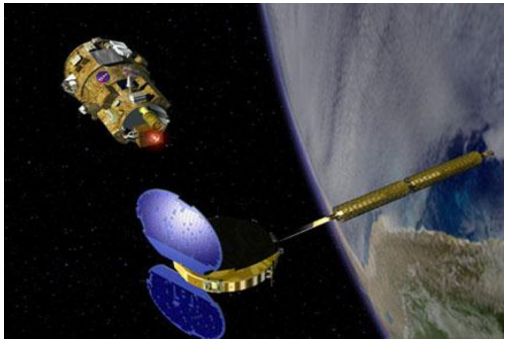
OOS Related Missions

(examples)

Russian Progress Vehicle

Japan ETS-7 Mission

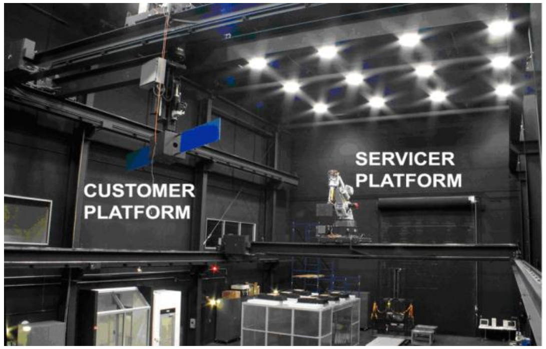
NASA DART Mission



ESA ATV Mission

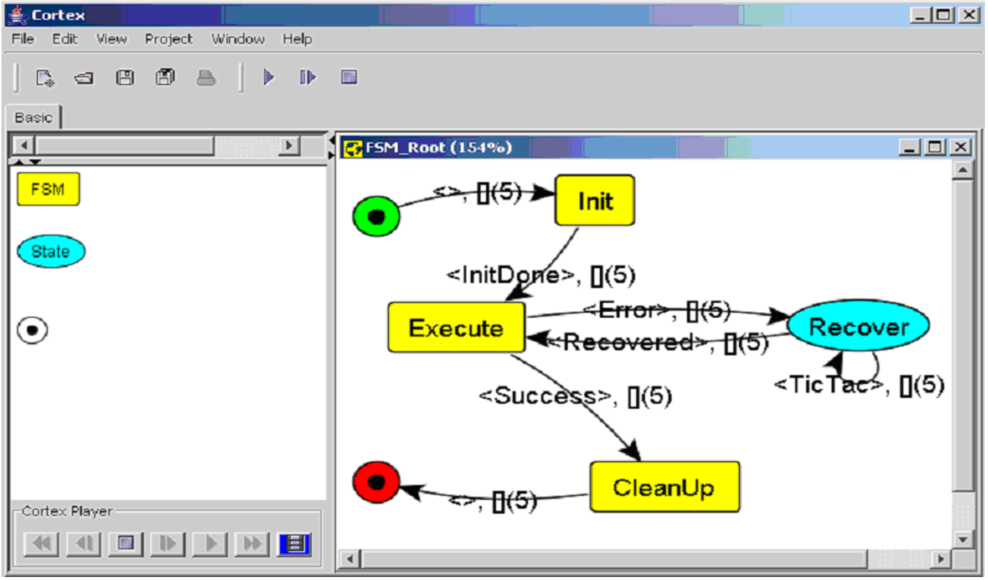
CX-OLEV Mission

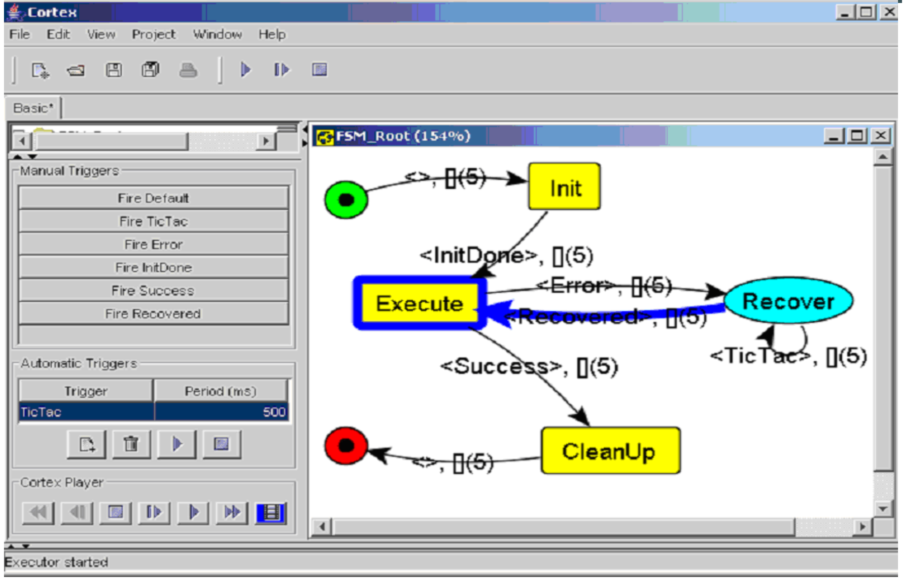
DARPA NRL SUMO Mission



Autonomous Control

- Toolbox for Reactive Autonomy
- Hierarchical Finite State Machines

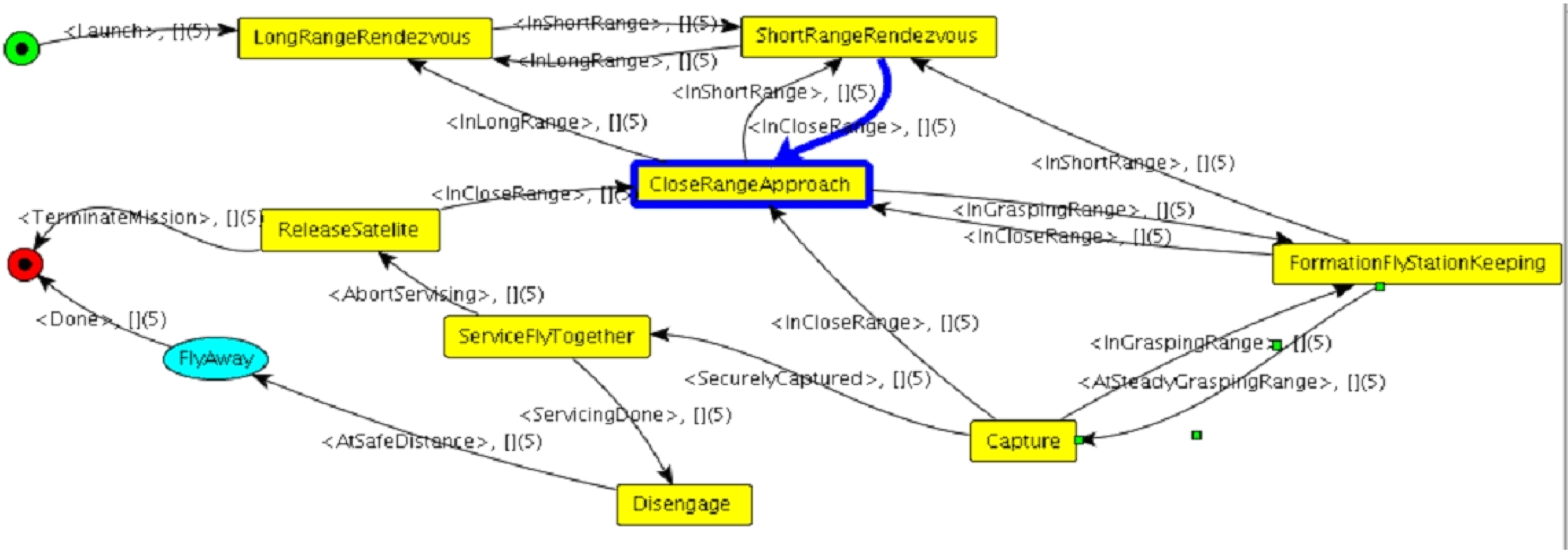




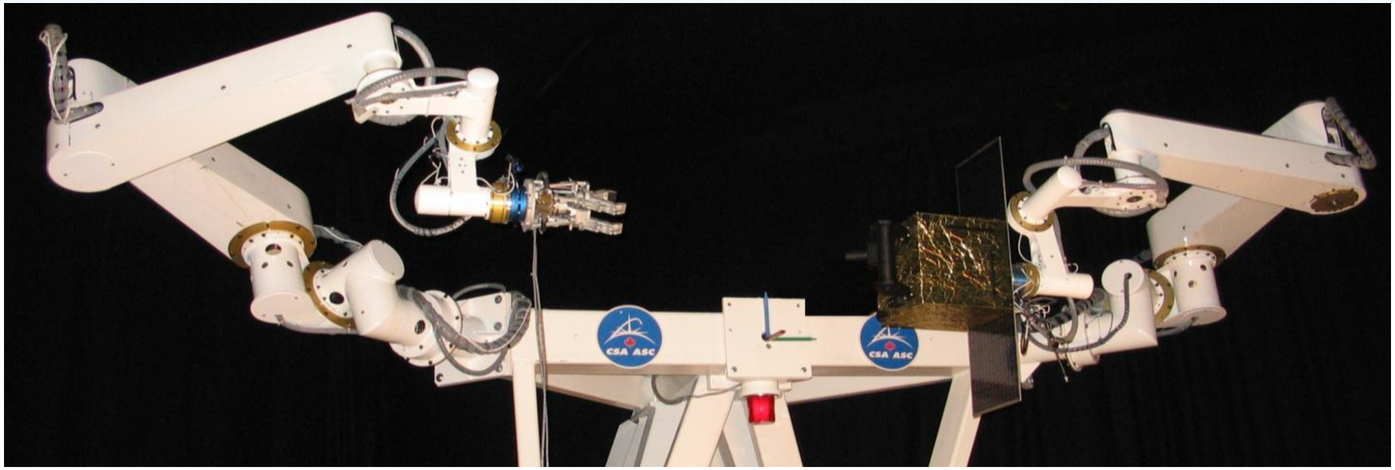
Trigger	Period (ms)
TicTac	500

Executor started

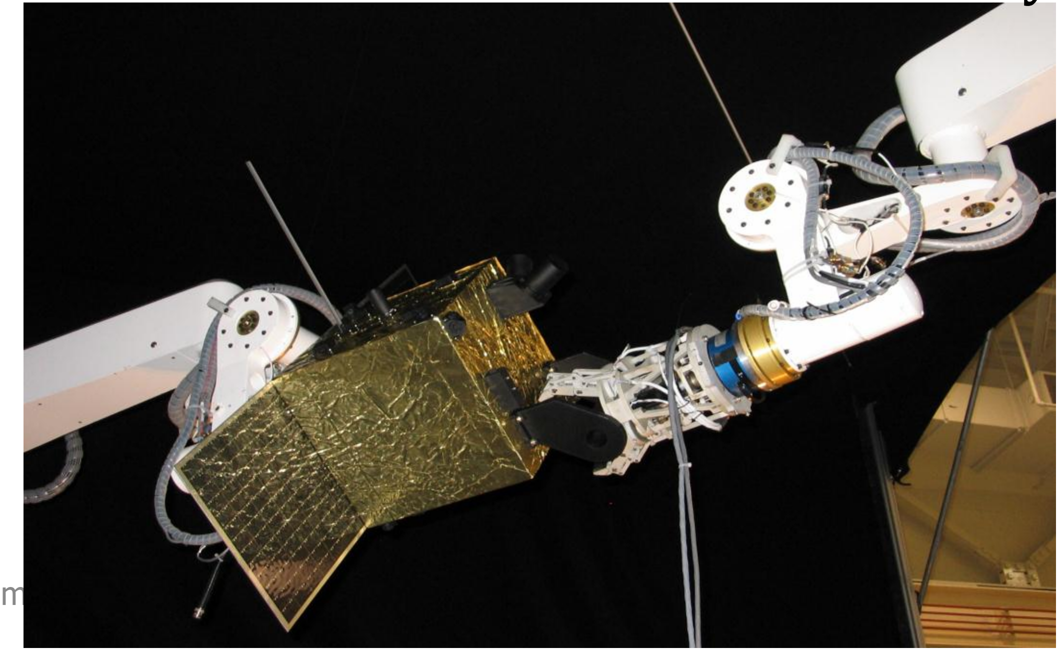
High-Level Scenario



Laboratory Setup

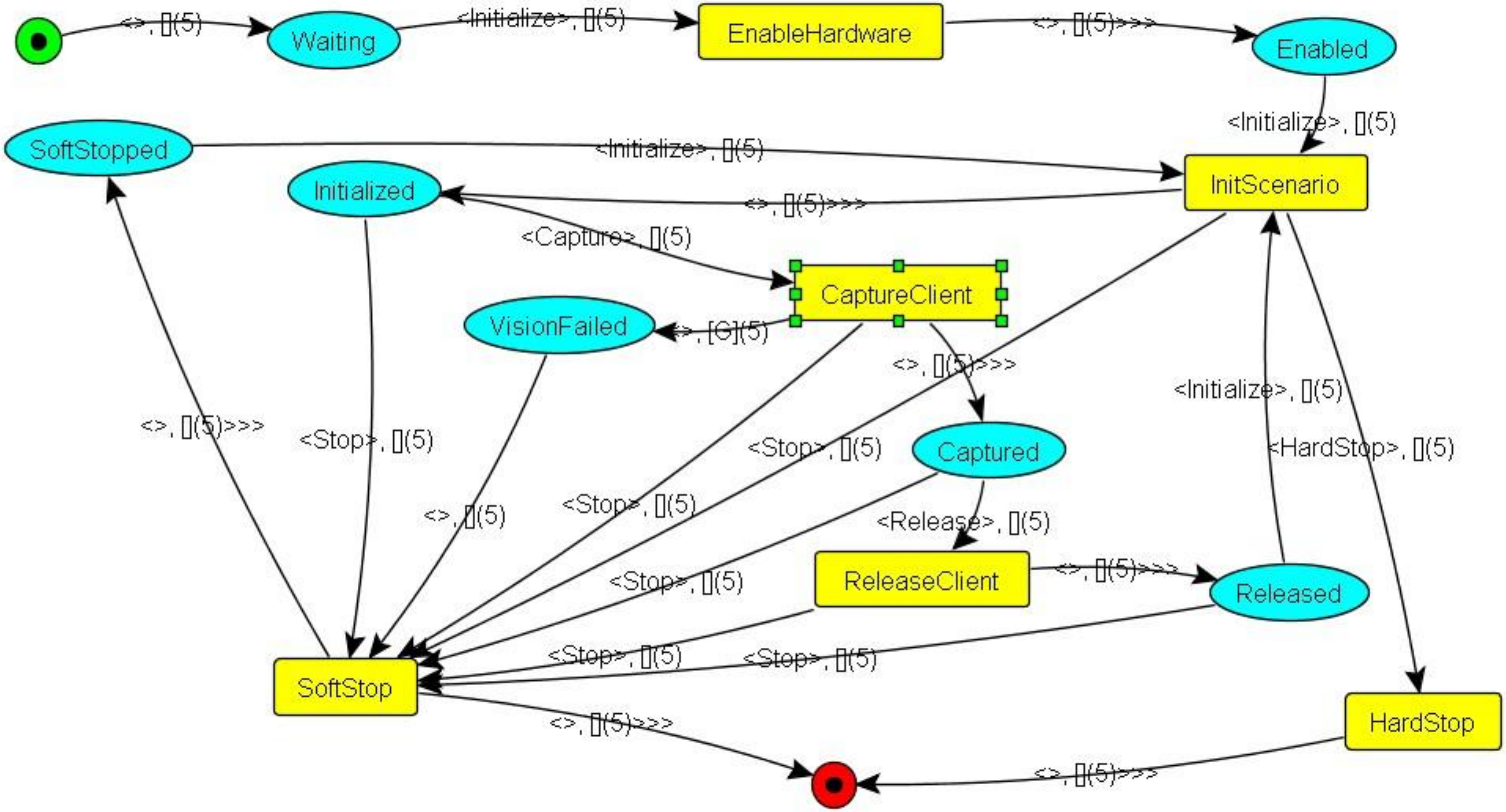


The SARAH hand from Laval University

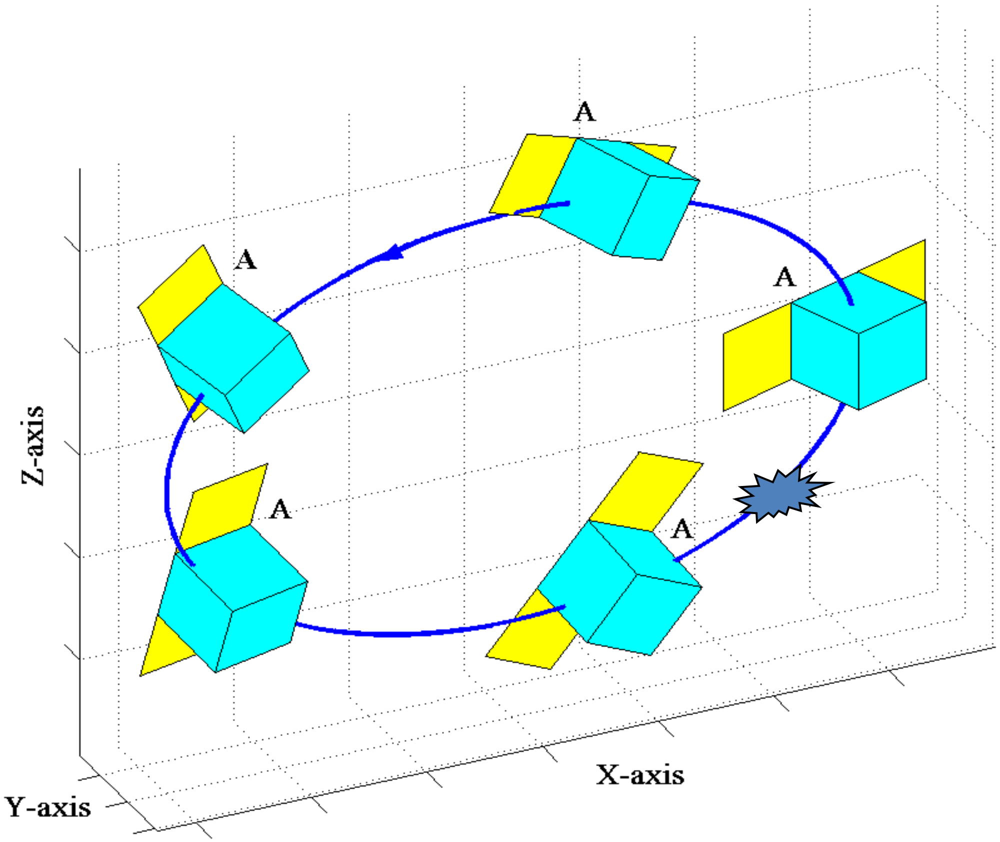


Laser Camera System (LCS), **Cape S/W** from Neptec

Autonomous Capture

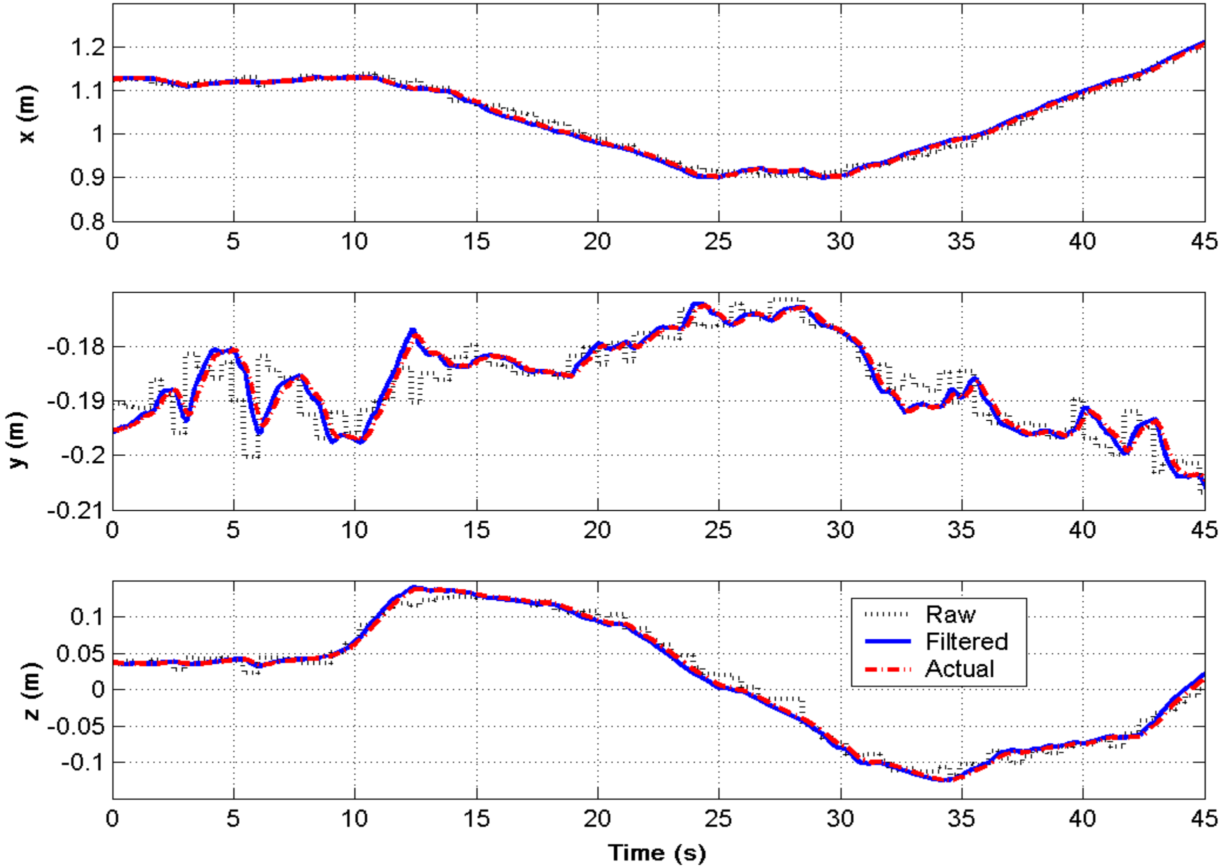


Trajectory Generation of the Target Satellite



Tracking

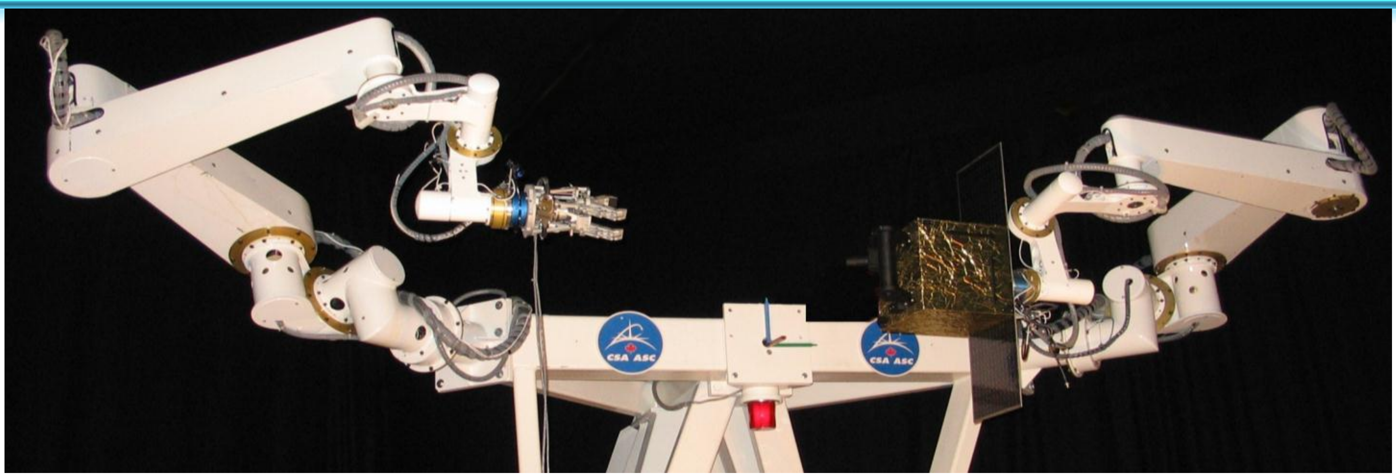
- A standard implementation of an extended Kalman Filter is used to track the pose of the target satellite
- Signal at 2Hz
- Delay of 1 step
- EKF prediction of 1 step



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

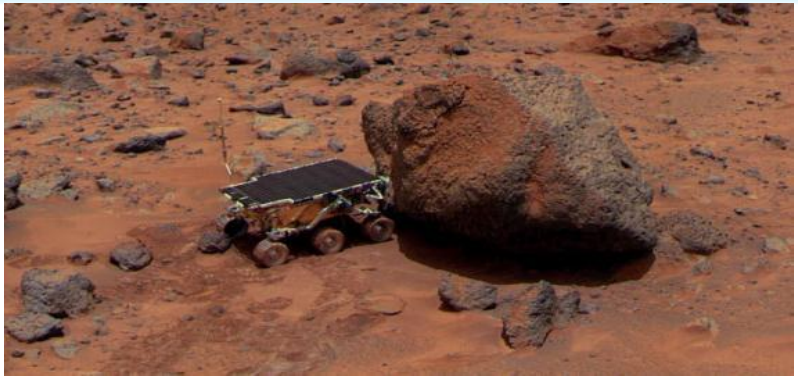
Planetary Exploration:

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

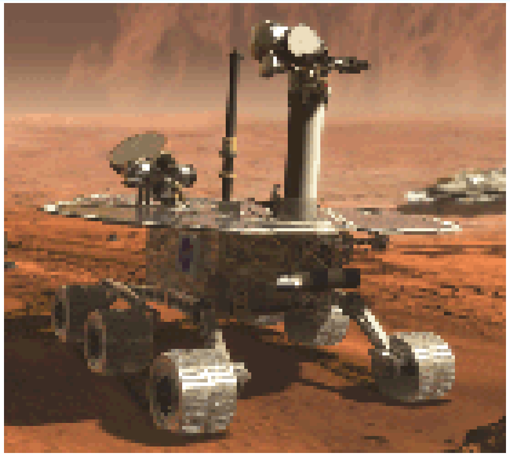
Outline

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

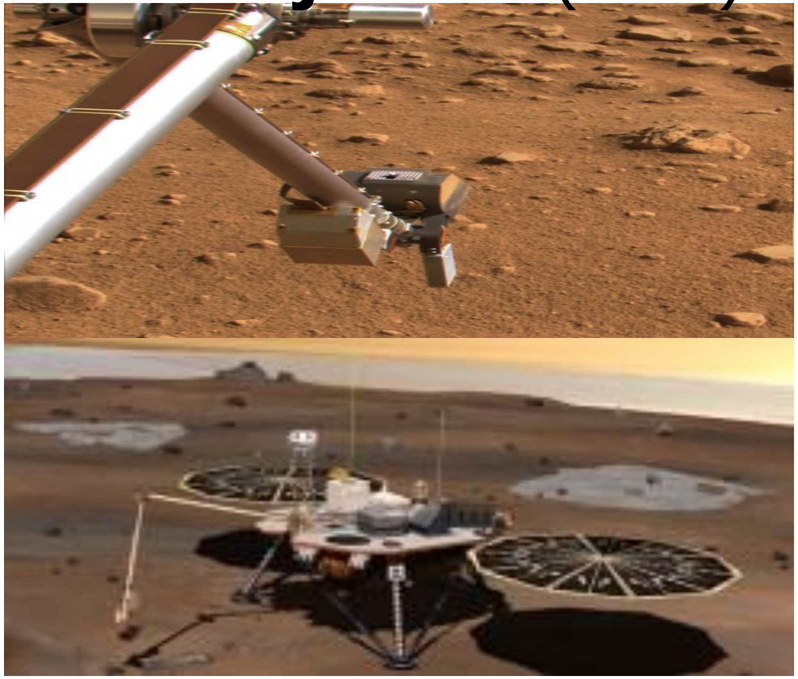
Exploring Mars



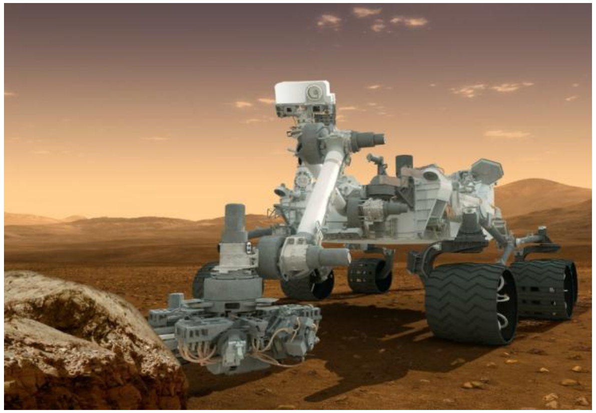
Sojourner (1997)



Spirit and **Opportunity** (2004)
Opportunity still running



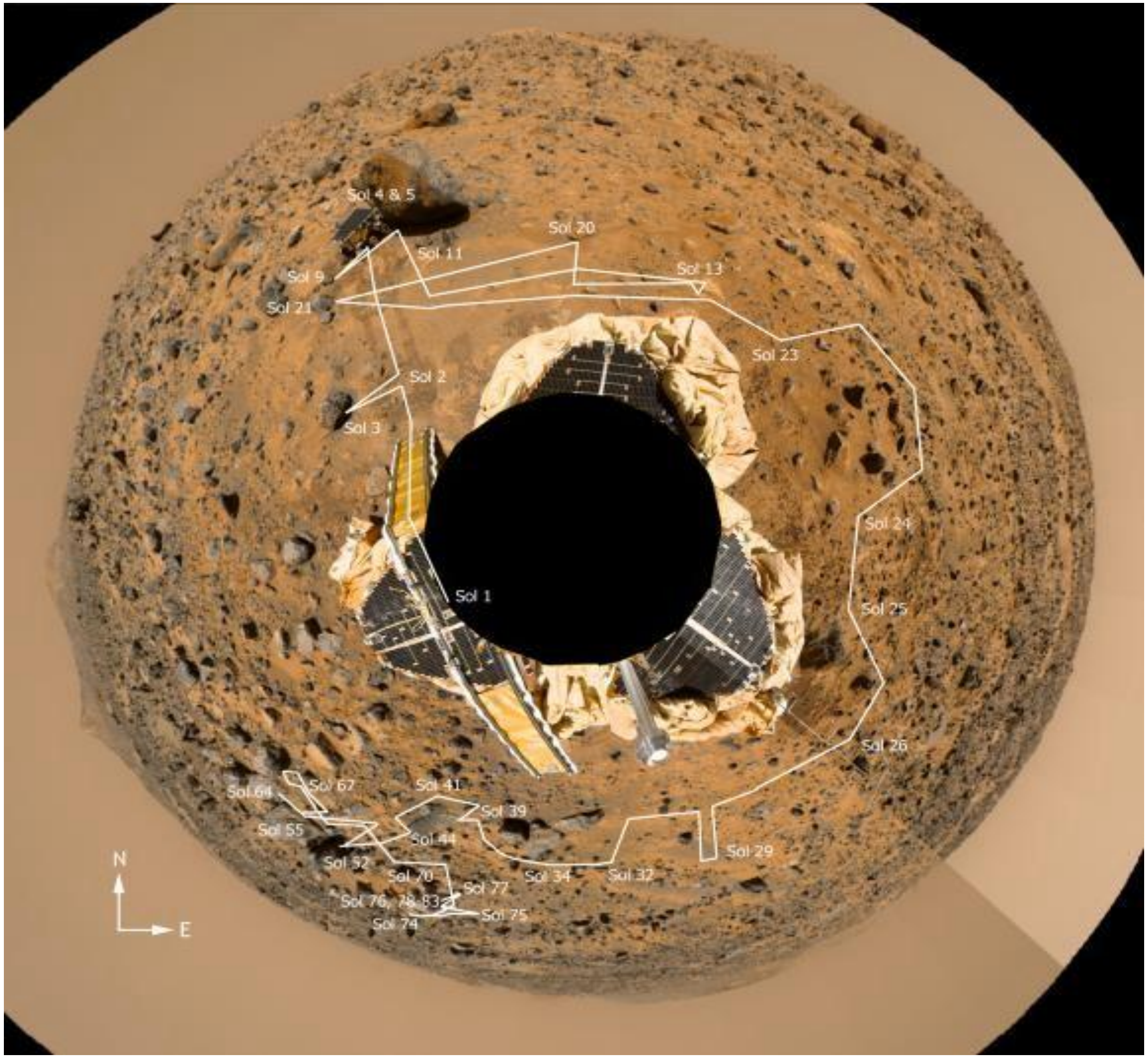
Phoenix (2008)



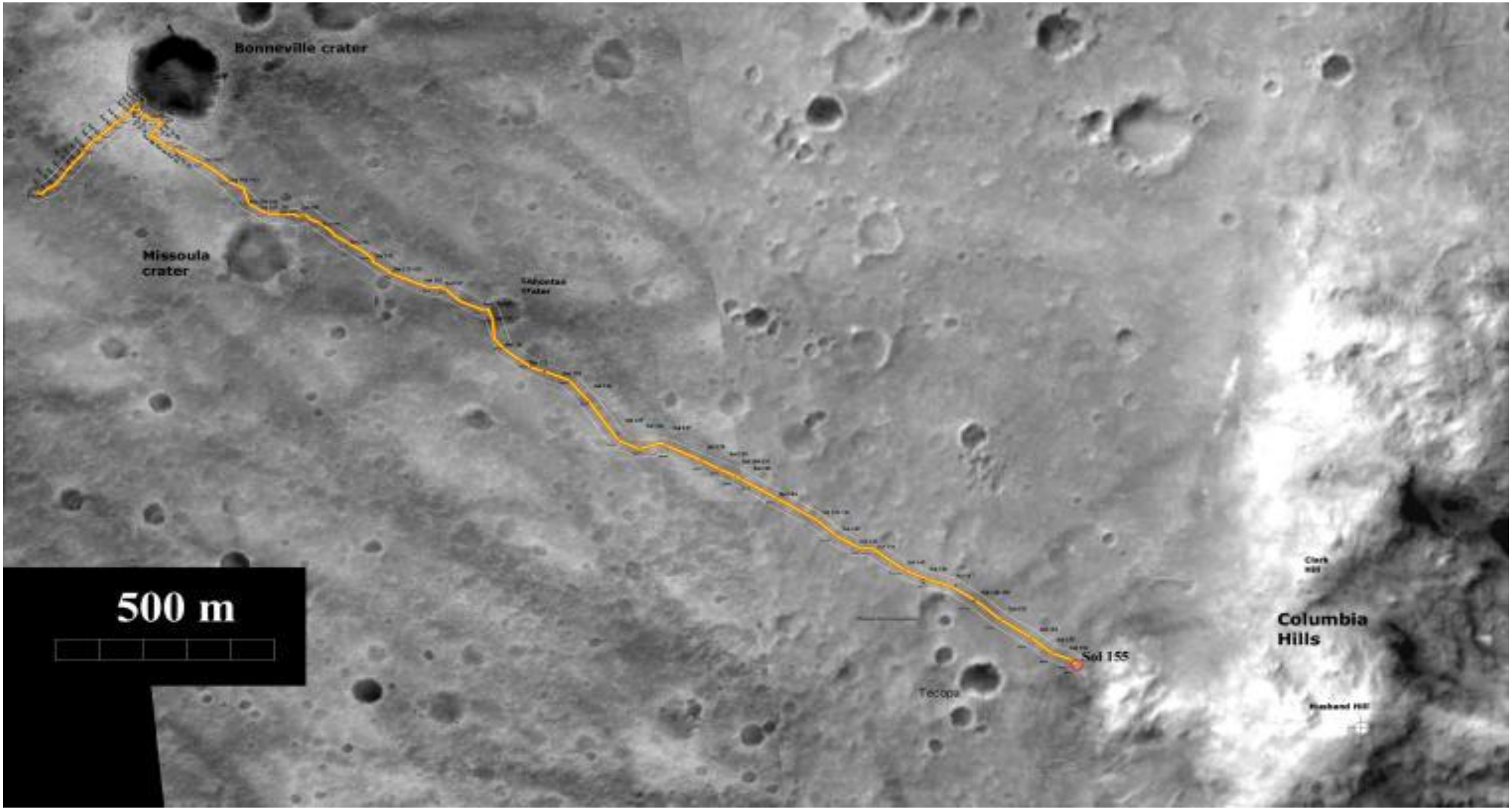
Mars Science Laboratory
Curiosity (2012)

View from Sojourner

Missions - Pathfinder 1997

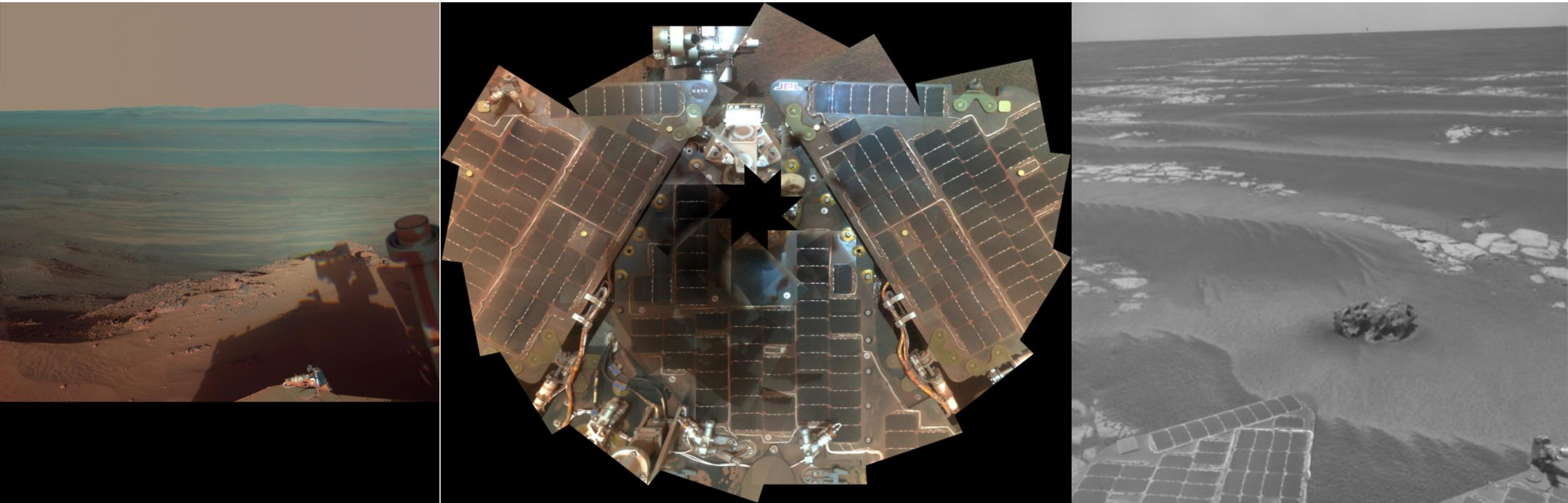


Missions – Spirit: Day 155

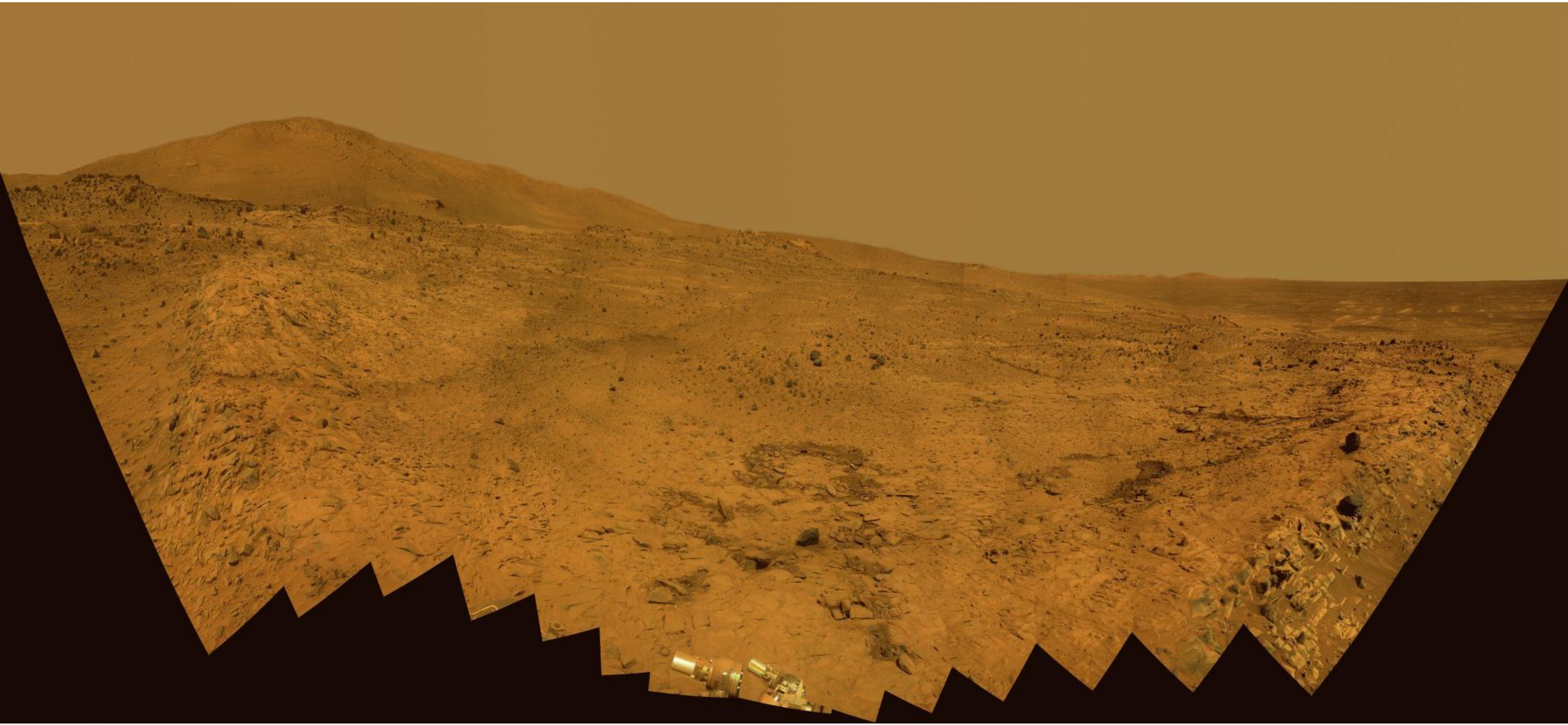


More Current Data

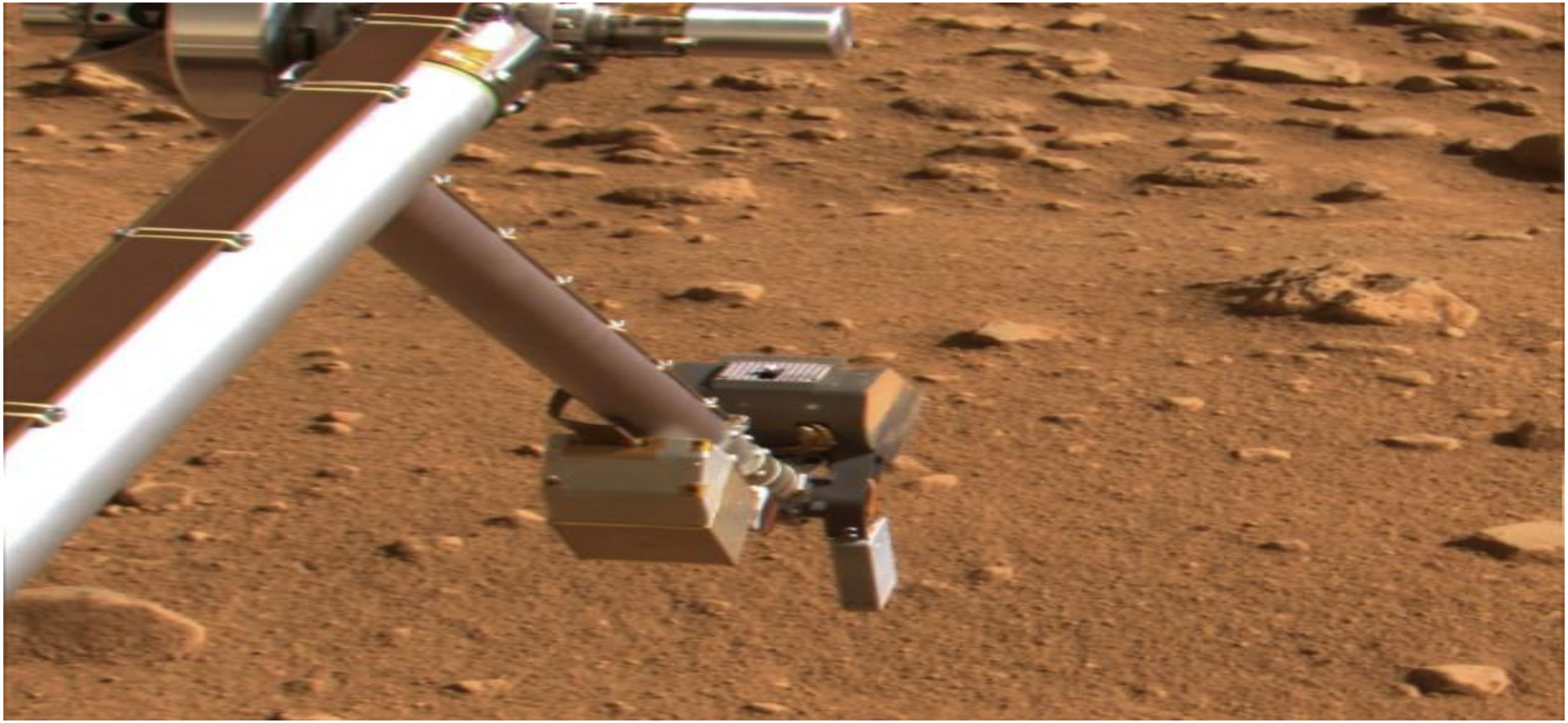
- **Opportunity**, Sol 3001 (July 03, 2012), 34.49 km
- **Spirit**, Sol 2210 (March 22, 2010), 7.7 km



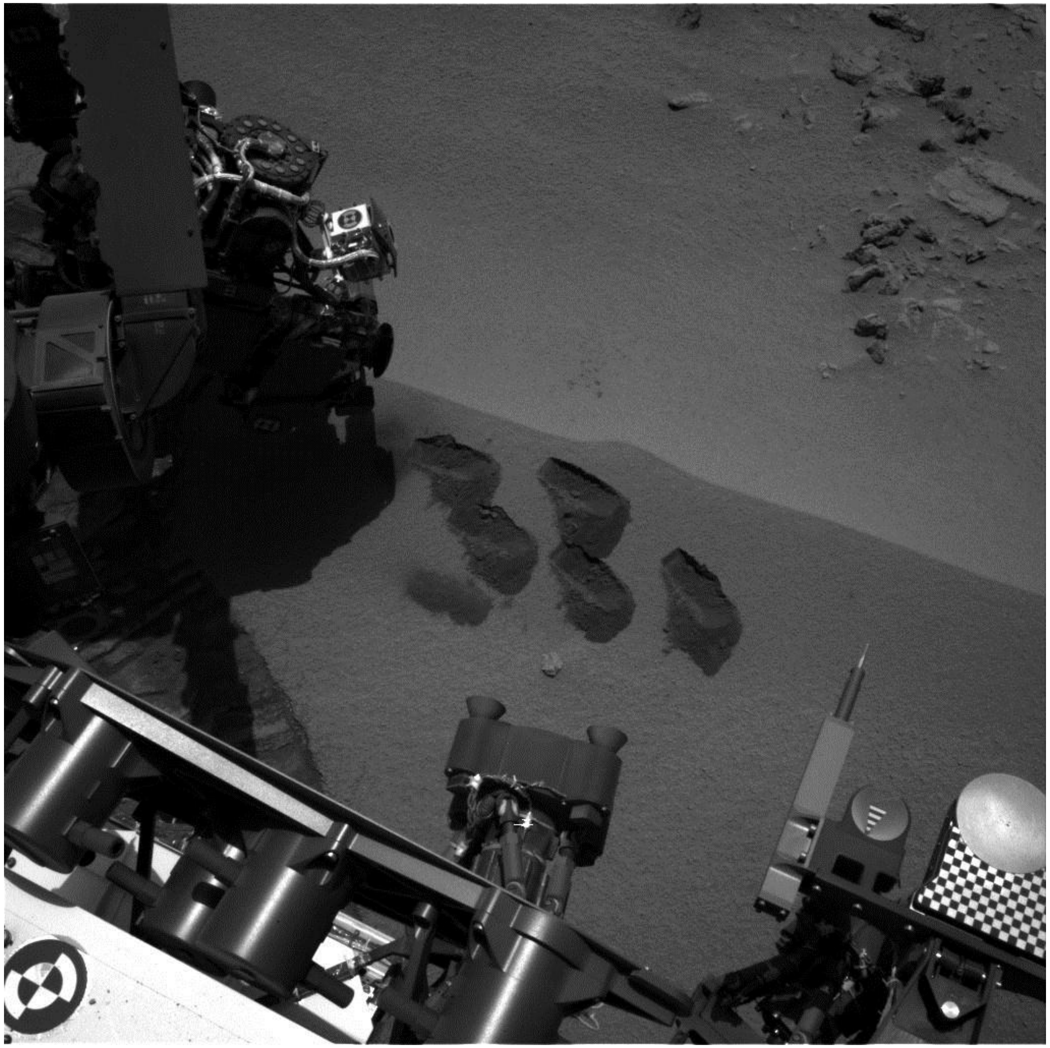
A Panorama from Spirit

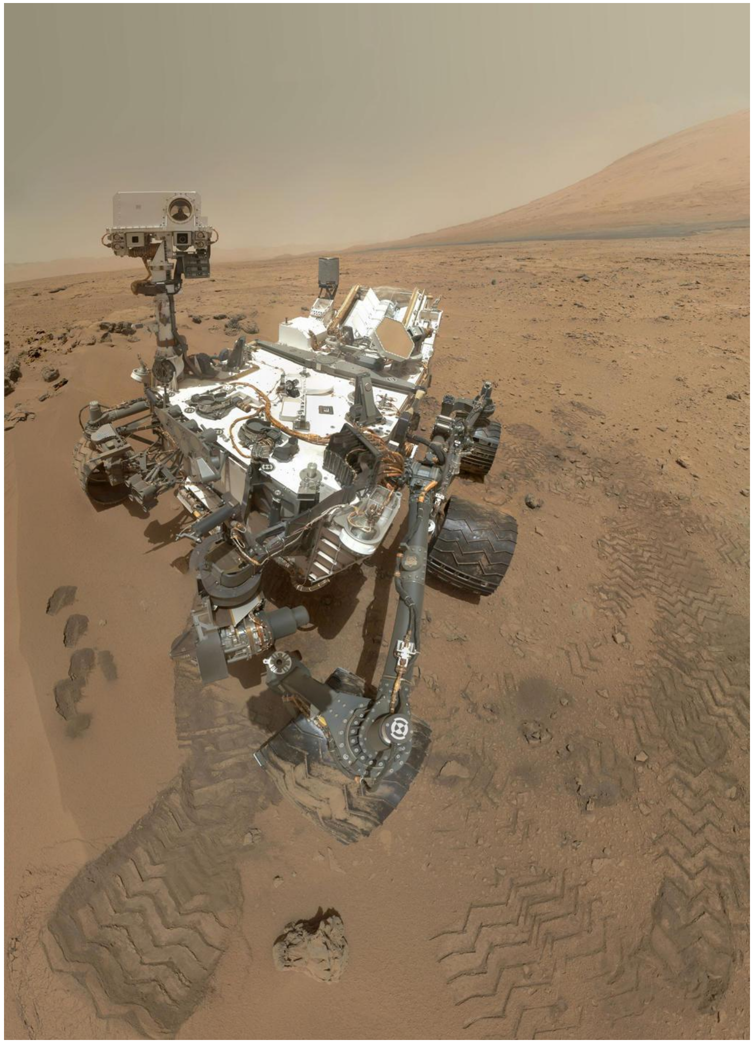


Phoenix in action



Mars Science Laboratory

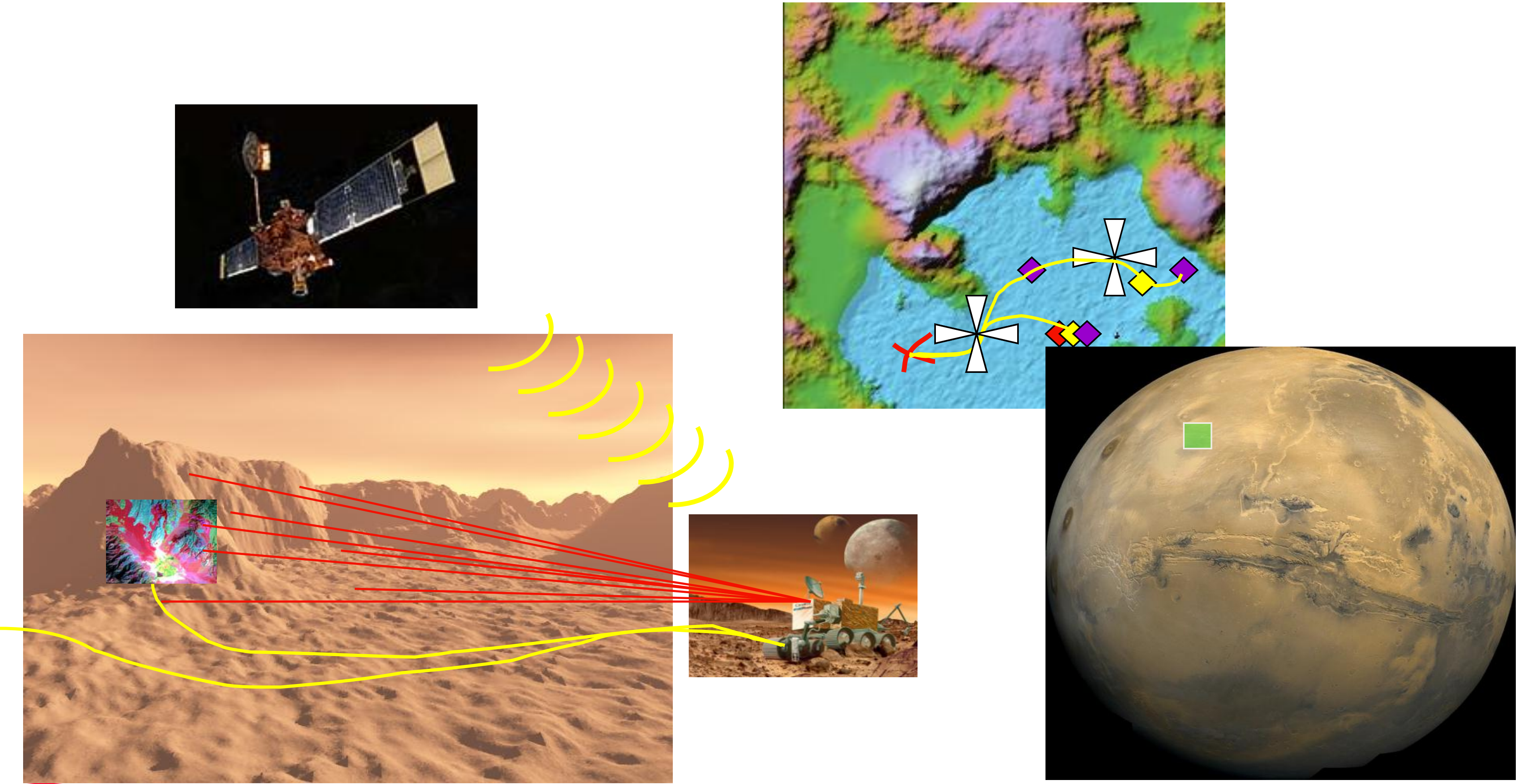




For more information visit:

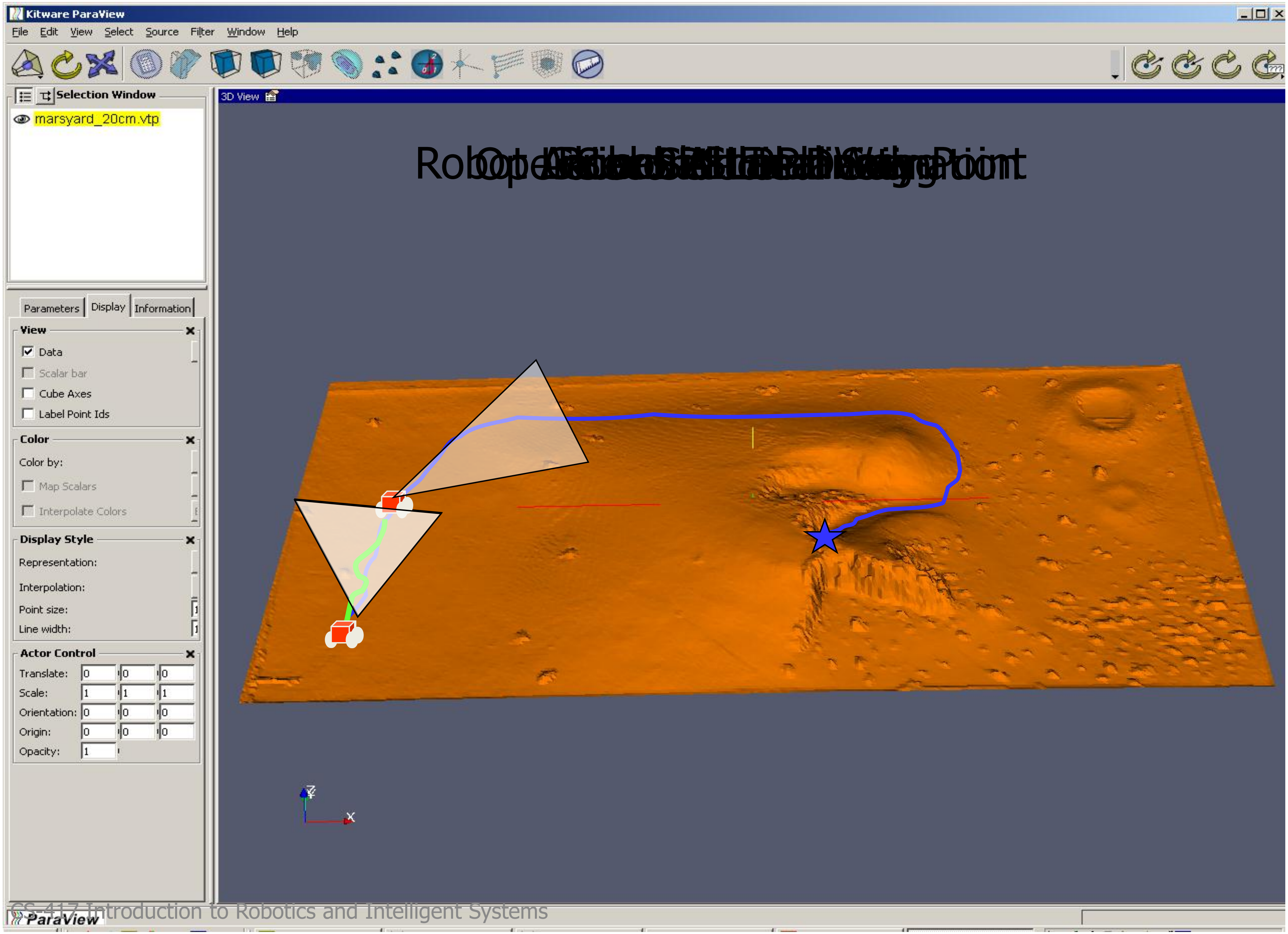
- http://mars.jpl.nasa.gov/msl/
- http://mars.jpl.nasa.gov/MPF/
- http://marsrovers.jpl.nasa.gov/home/
- http://phoenix.lpl.arizona.edu/index.php
- http://www.google.com/mars/

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



marsyard_20cm.vtp

Parameters | Display | Information

View

☑ Data
☐ Scalar bar
☐ Cube Axes
☐ Label Point Ids

Color

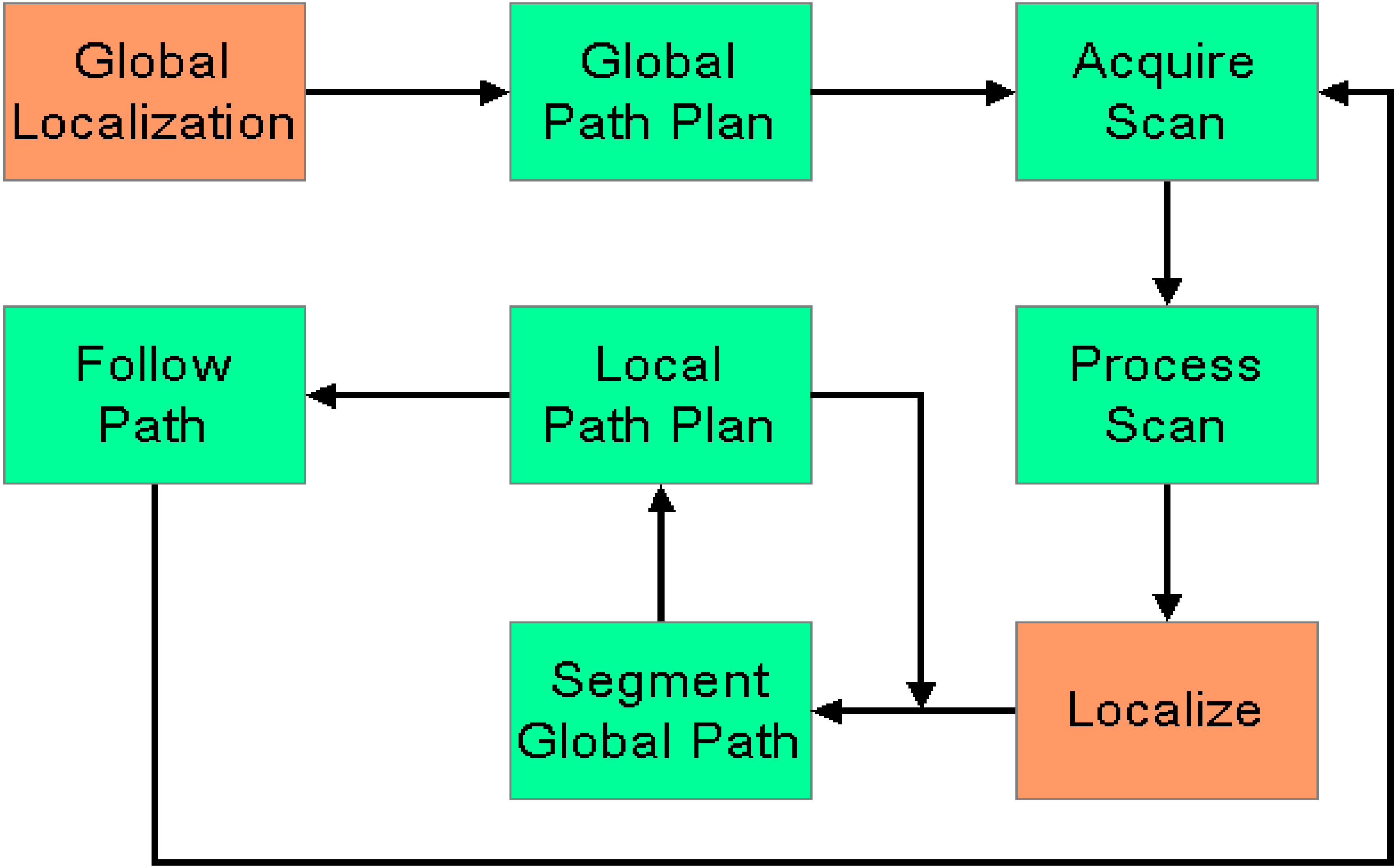
Color by:
☐ Map Scalars
☐ Interpolate Colors

Display Style

Representation:
Interpolation:
Point size:
Line width:

Actor Control

Translate:	0	0	0
Scale:	1	1	1
Orientation:	0	0	0
Origin:	0	0	0
Opacity:	1		


Global Localization

Global Path Plan

Acquire Scan

Process Scan

Localize

Segment Global Path

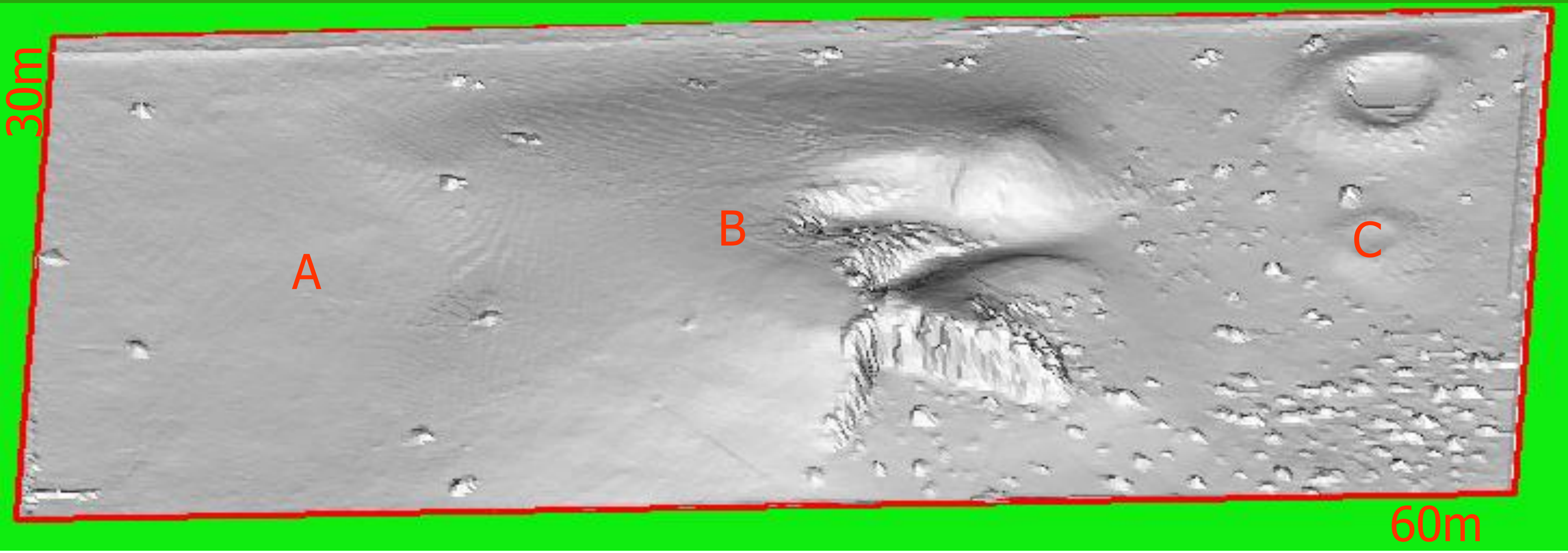
Local Path Plan

Follow Path

Experimental Testbed 2006

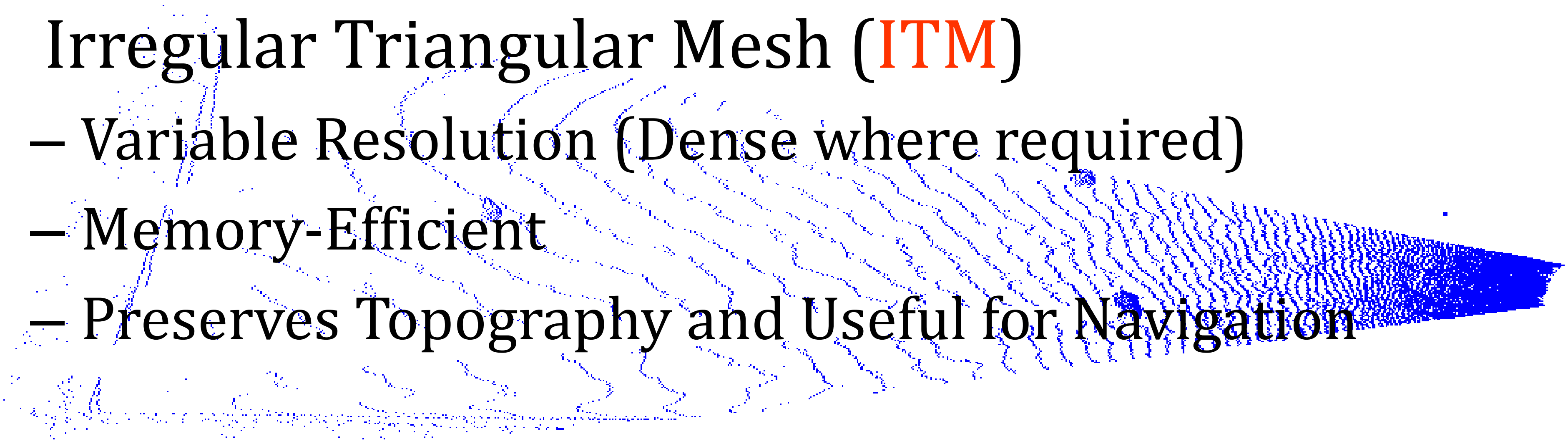
- CSA Mars Terrain
  - 60m x 30m
- Pioneer P2-AT Robot
- ILRIS-3D LIDAR
  - 3D point cloud
  - 1.5km-range (trimmed down to ~30m)
  - 40 degree FOV

Mars Emulation Terrain

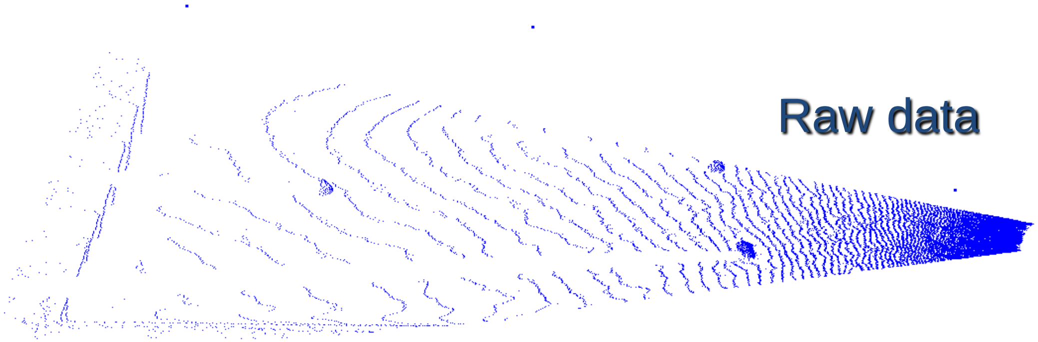


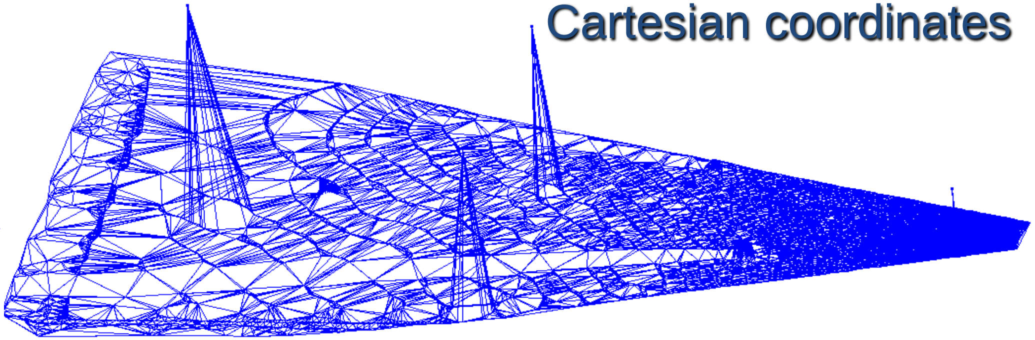
Terrain Modeling

- 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

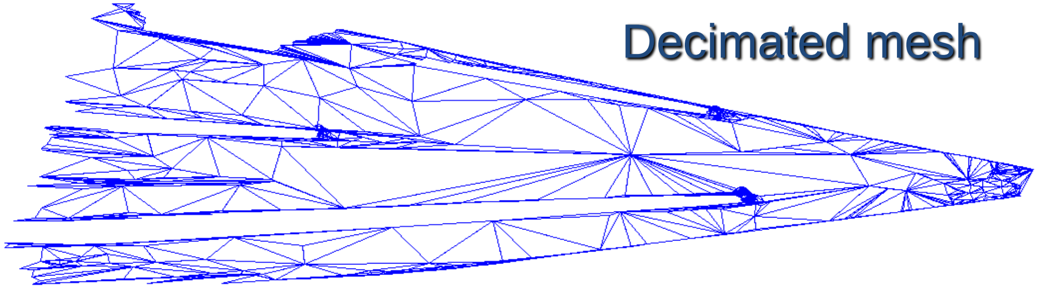


Terrain Modeling:
Irregular Triangular Mesh (ITM)

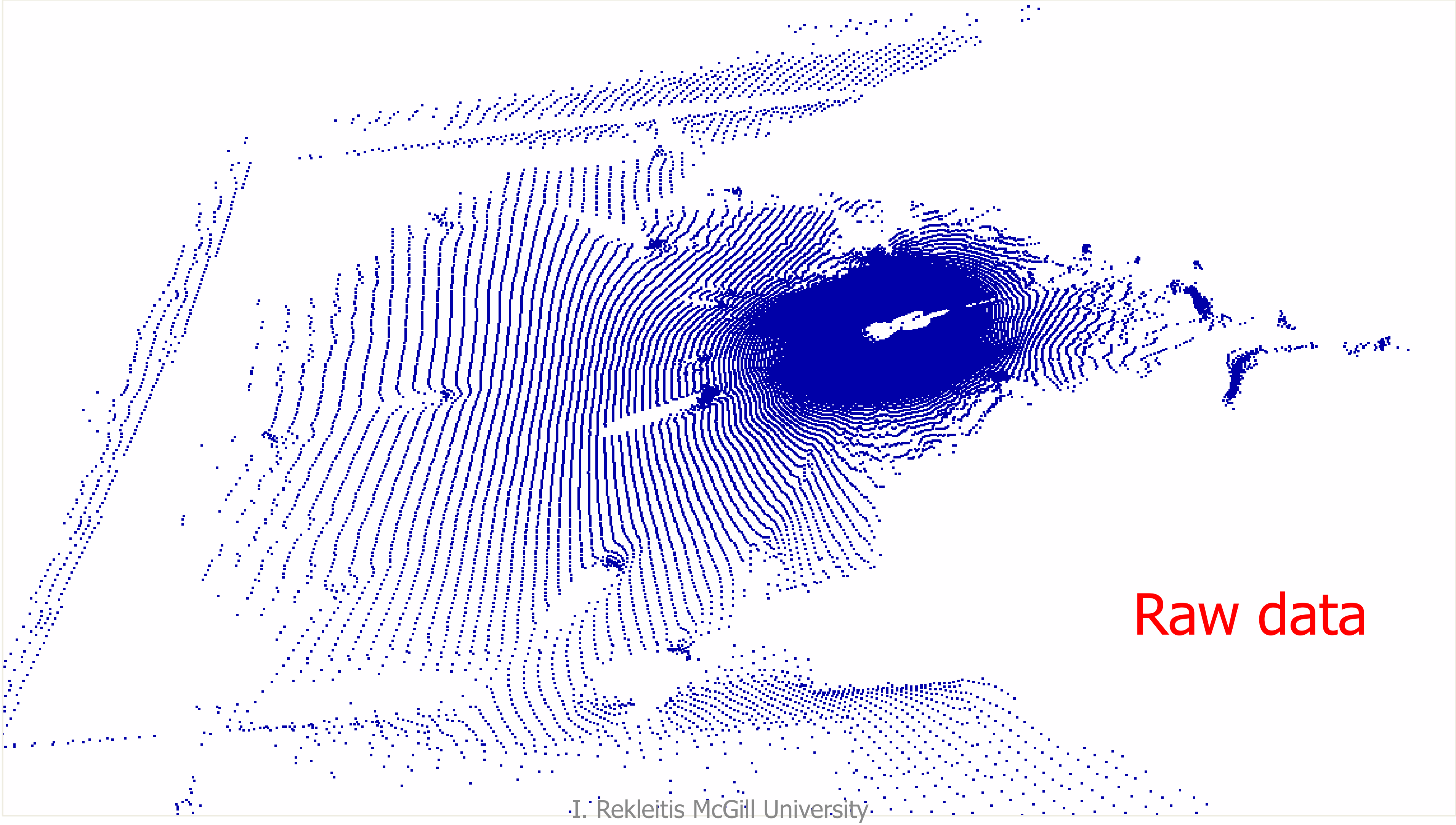

Raw data


Delaunay triangulation,
Cartesian coordinates


Delaunay triangulation,
polar coordinates

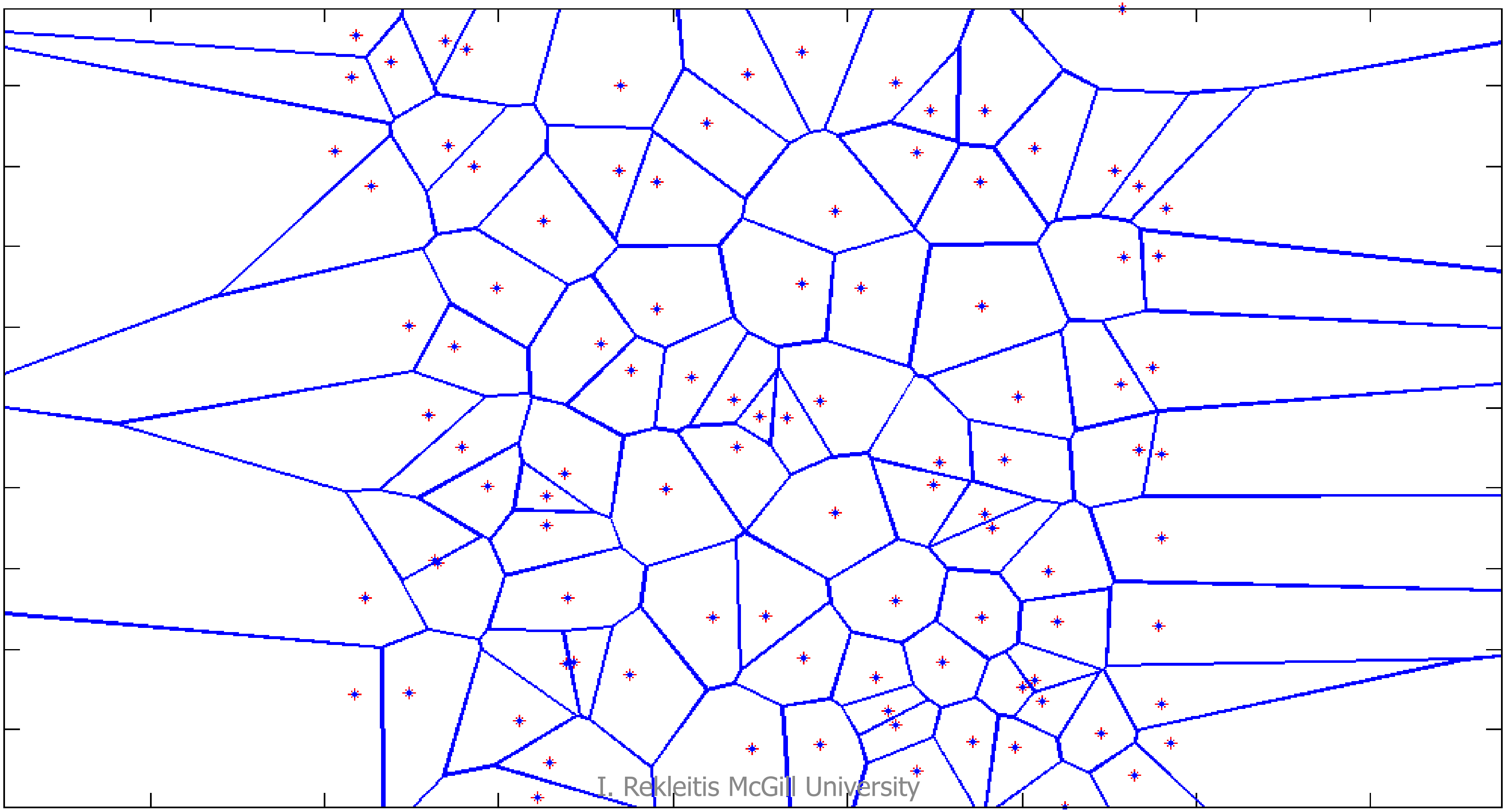

Decimated mesh

Terrain Modeling:
Irregular Triangular Mesh (ITM)


Raw data

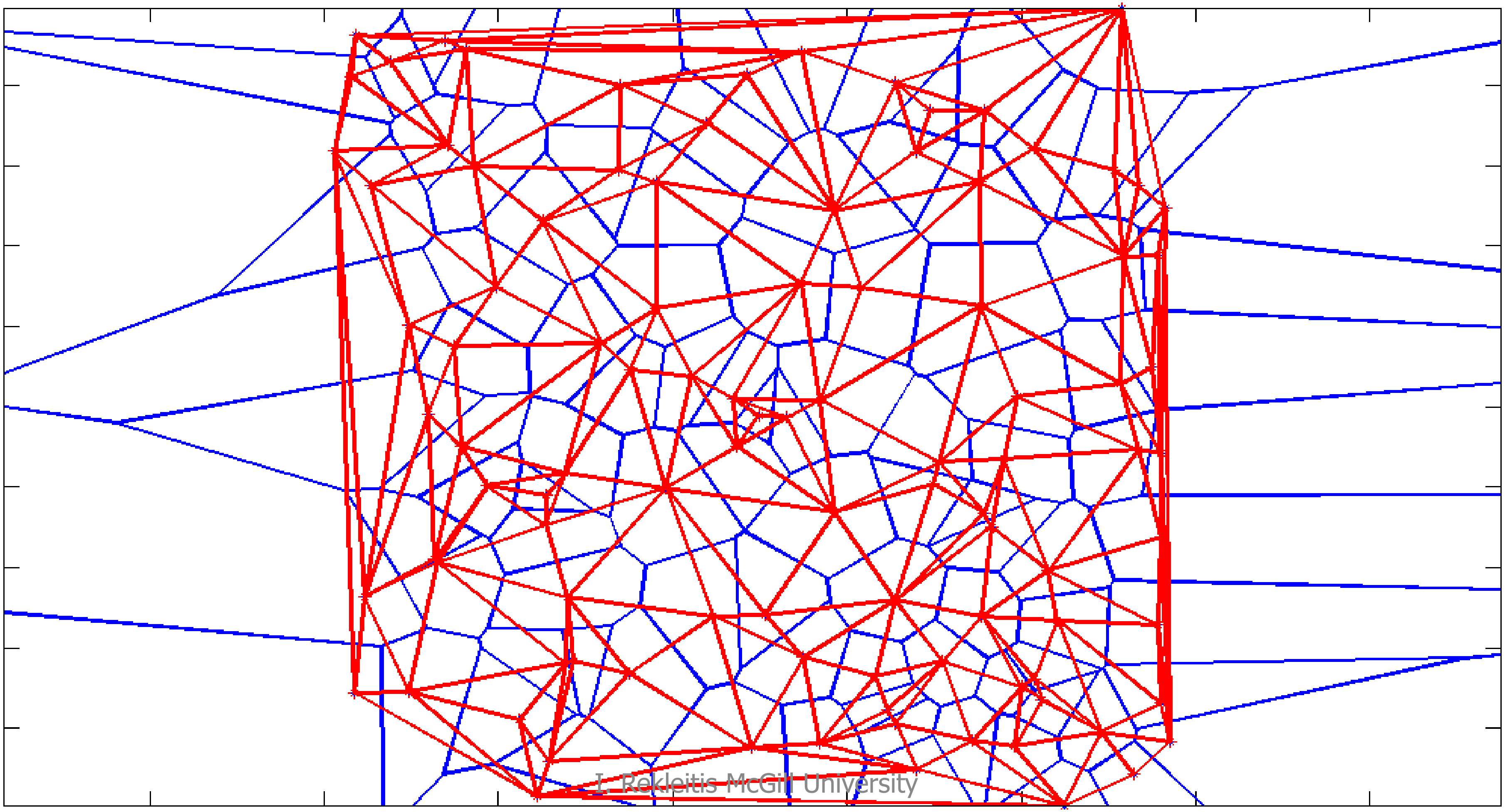
Voronoi Diagrams

For each point in the input set group all the points that are closer to it than any other input point.



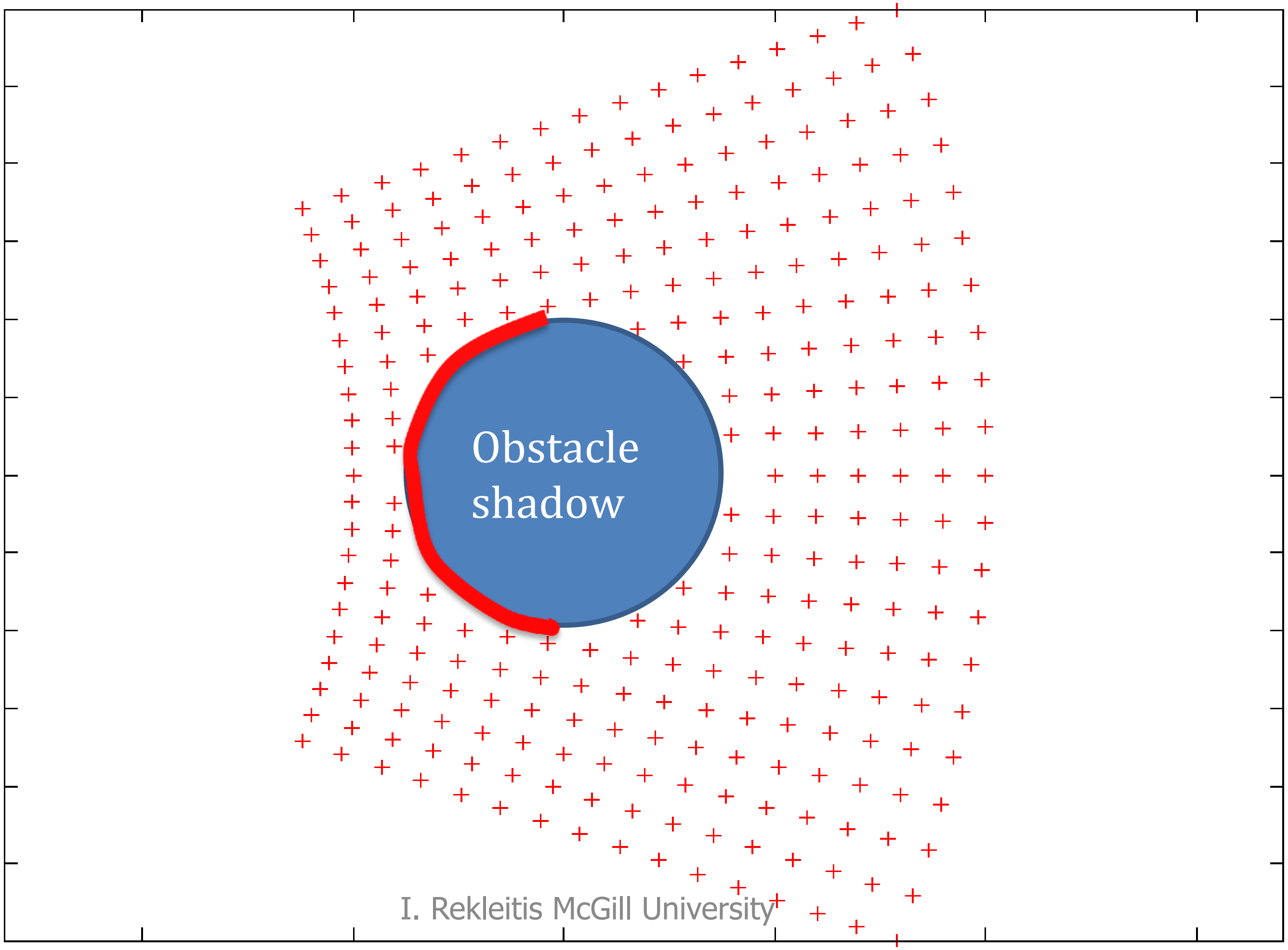
Delaunay Triangulation

Adjacent cells are connected with an edge.



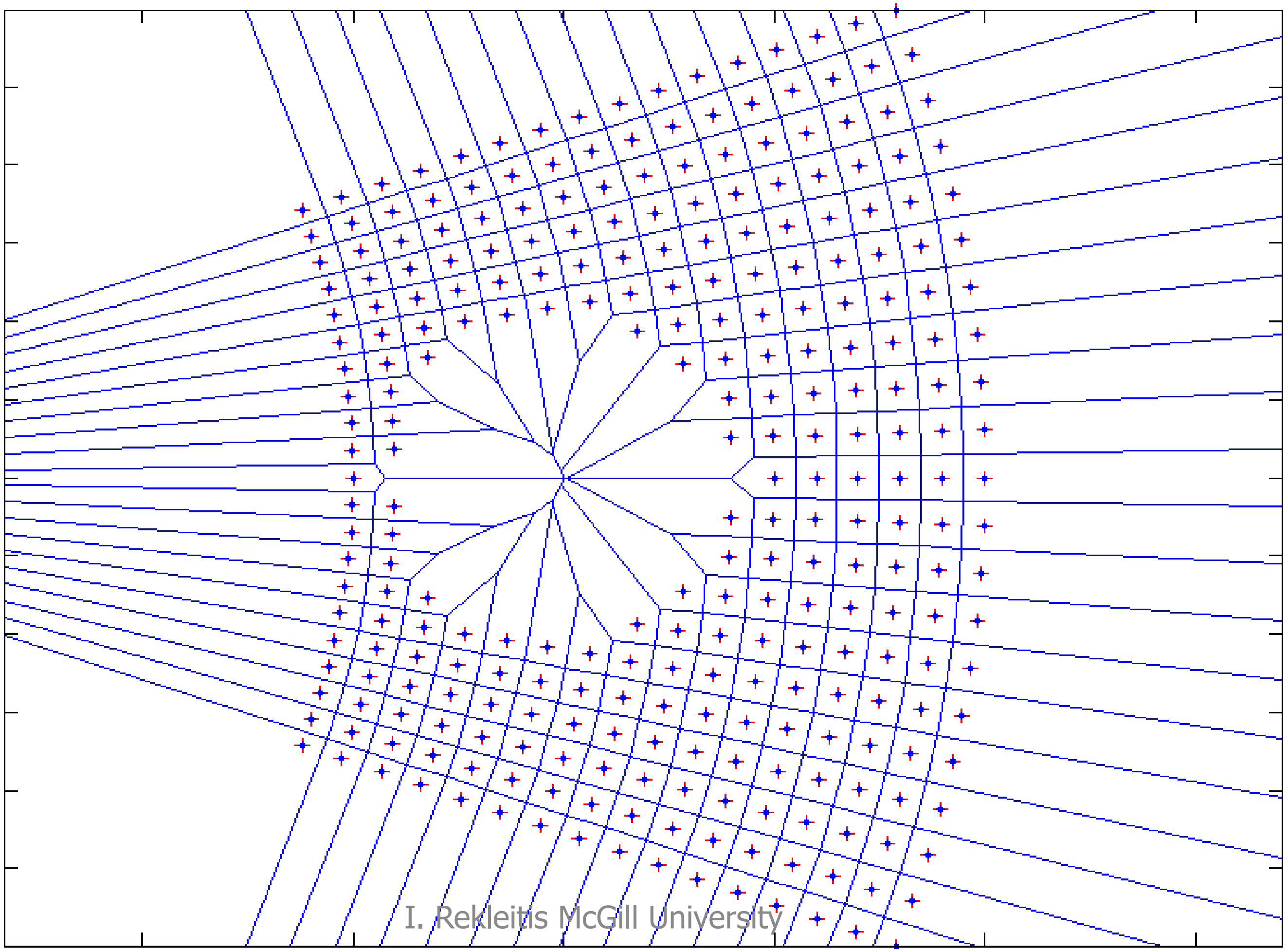
Simulated Scan

Raw data:



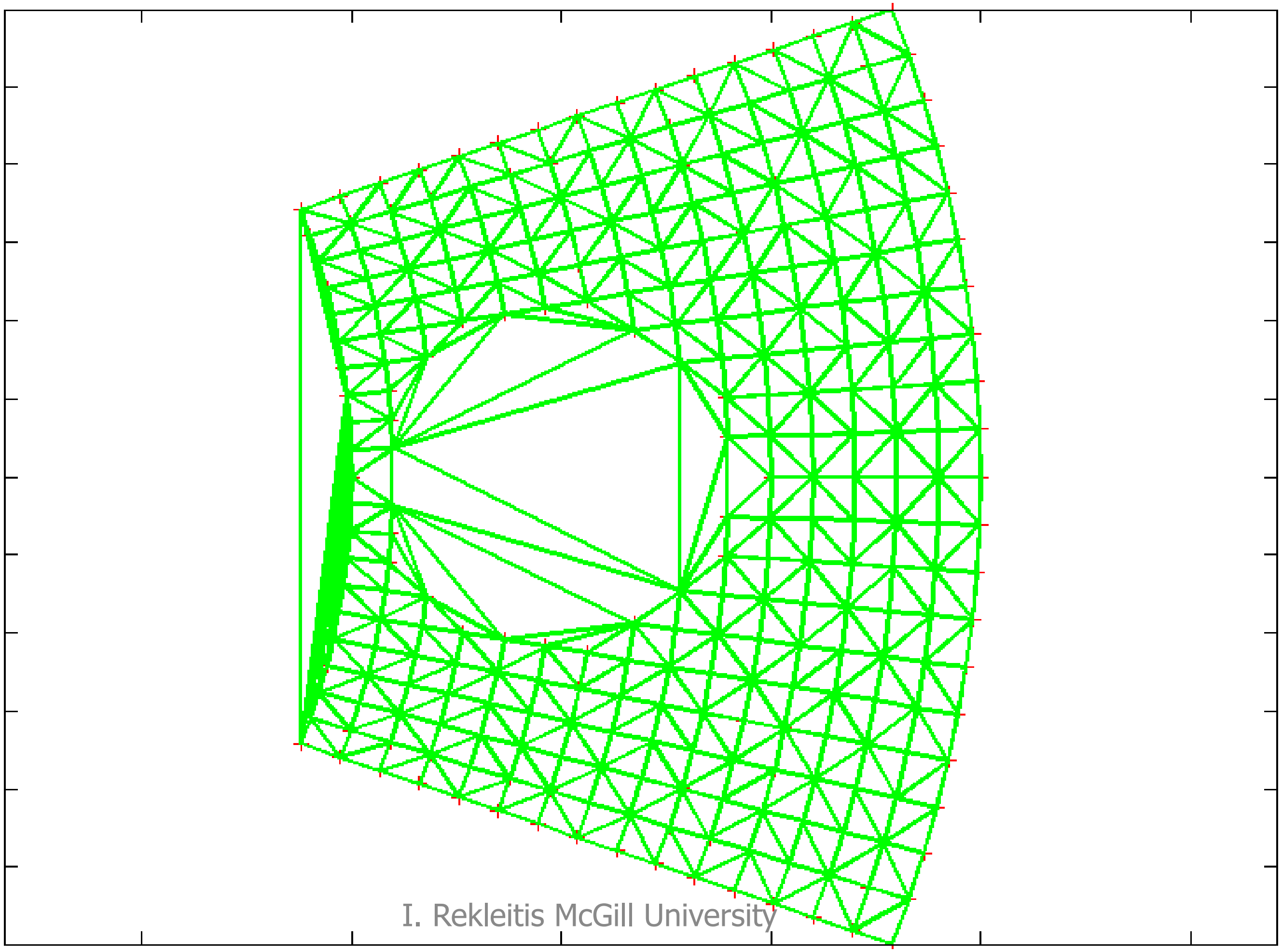
Simulated Scan

Voronoi Diagram



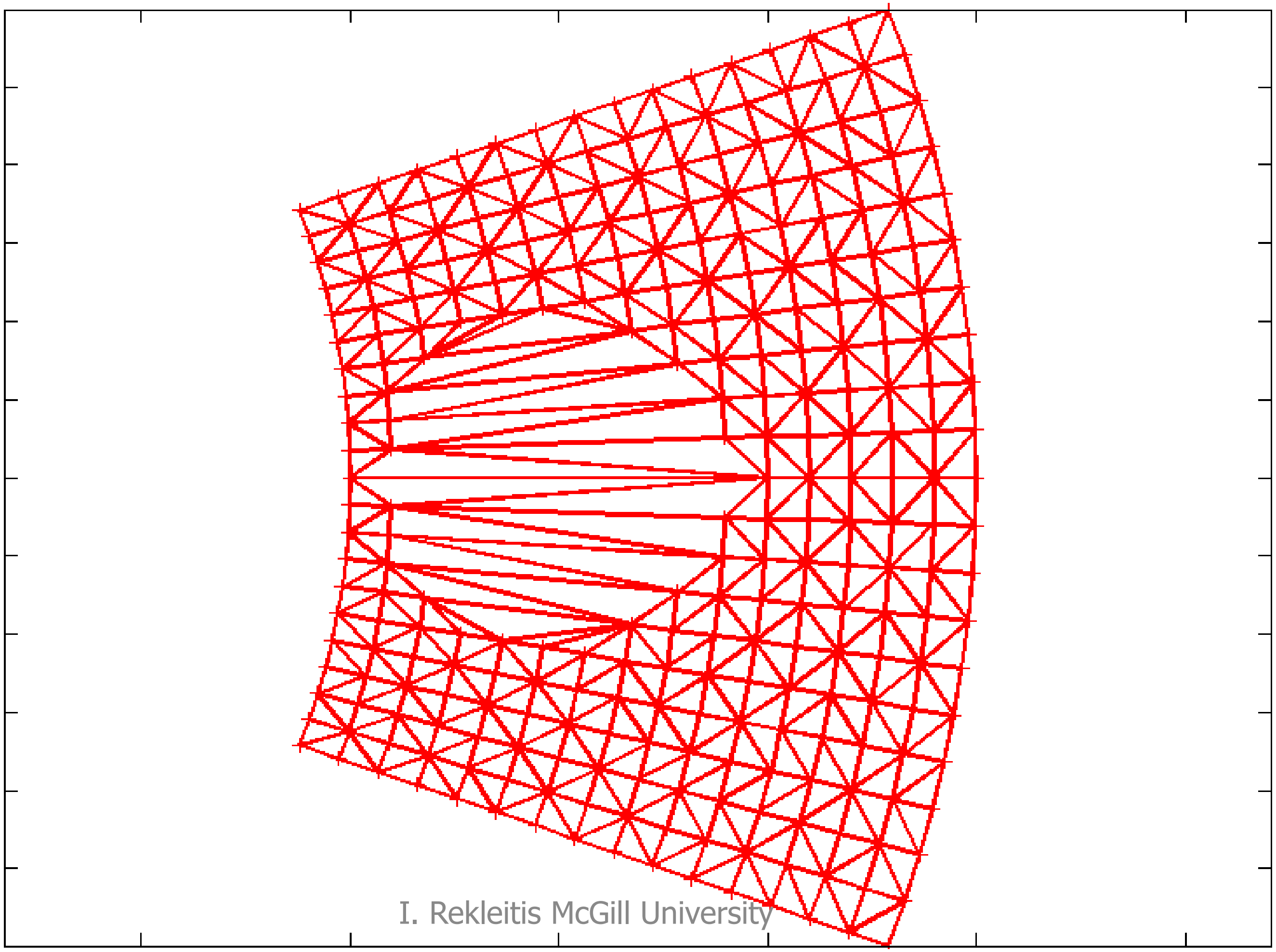
Simulated Scan

Delaunay Triangulation (Cartesian Coordinates)



Simulated Scan

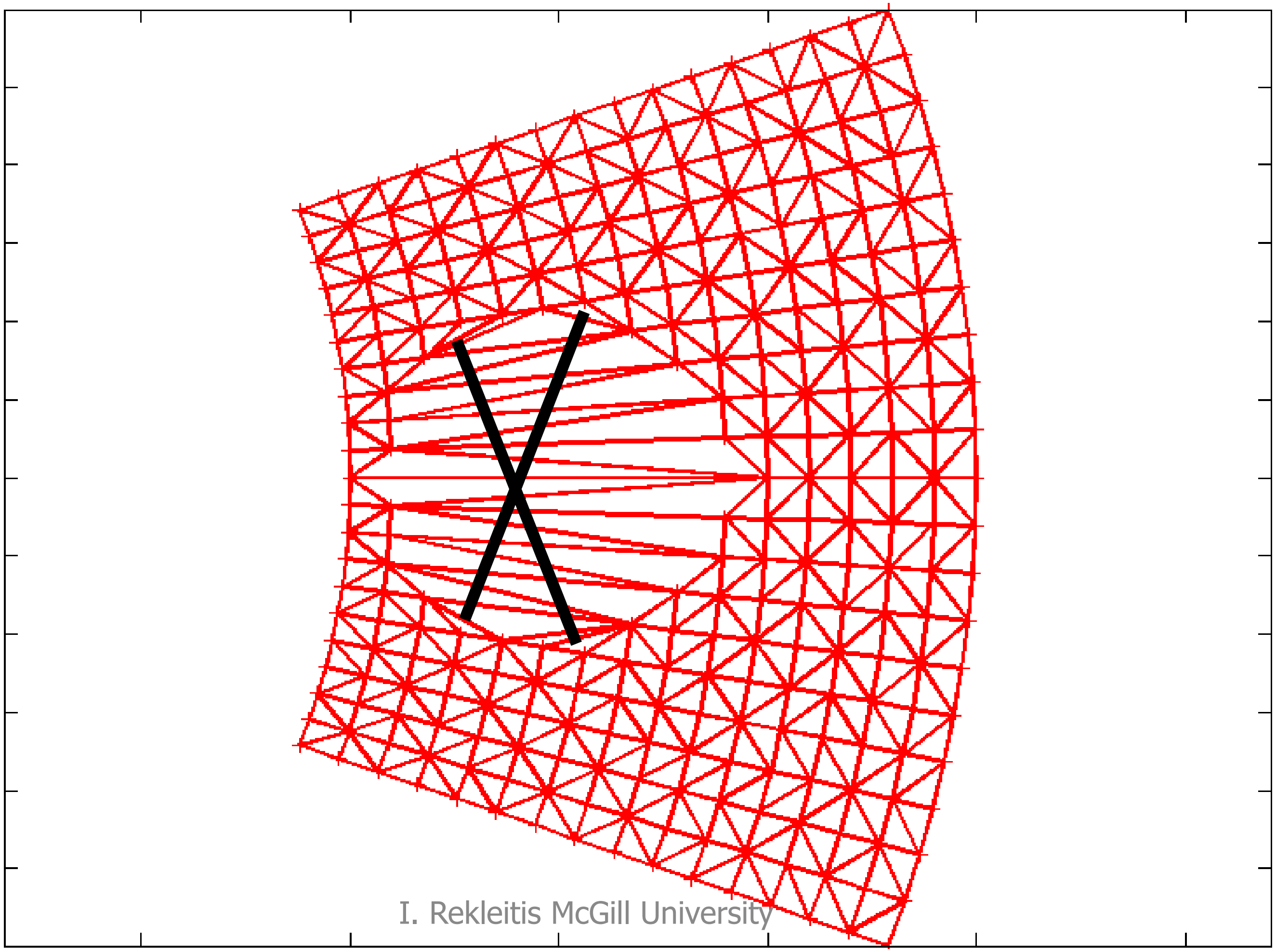
Delaunay Triangulation (Spherical Coordinates)



Simulated Scan

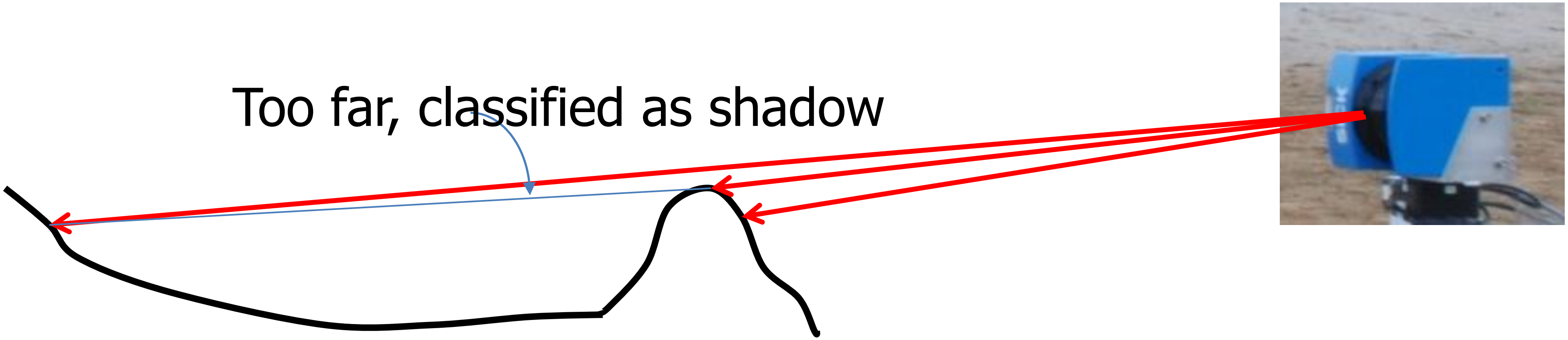
Delaunay Triangulation (Spherical Coordinates)

-Remove triangles from shadows (use 3D information)

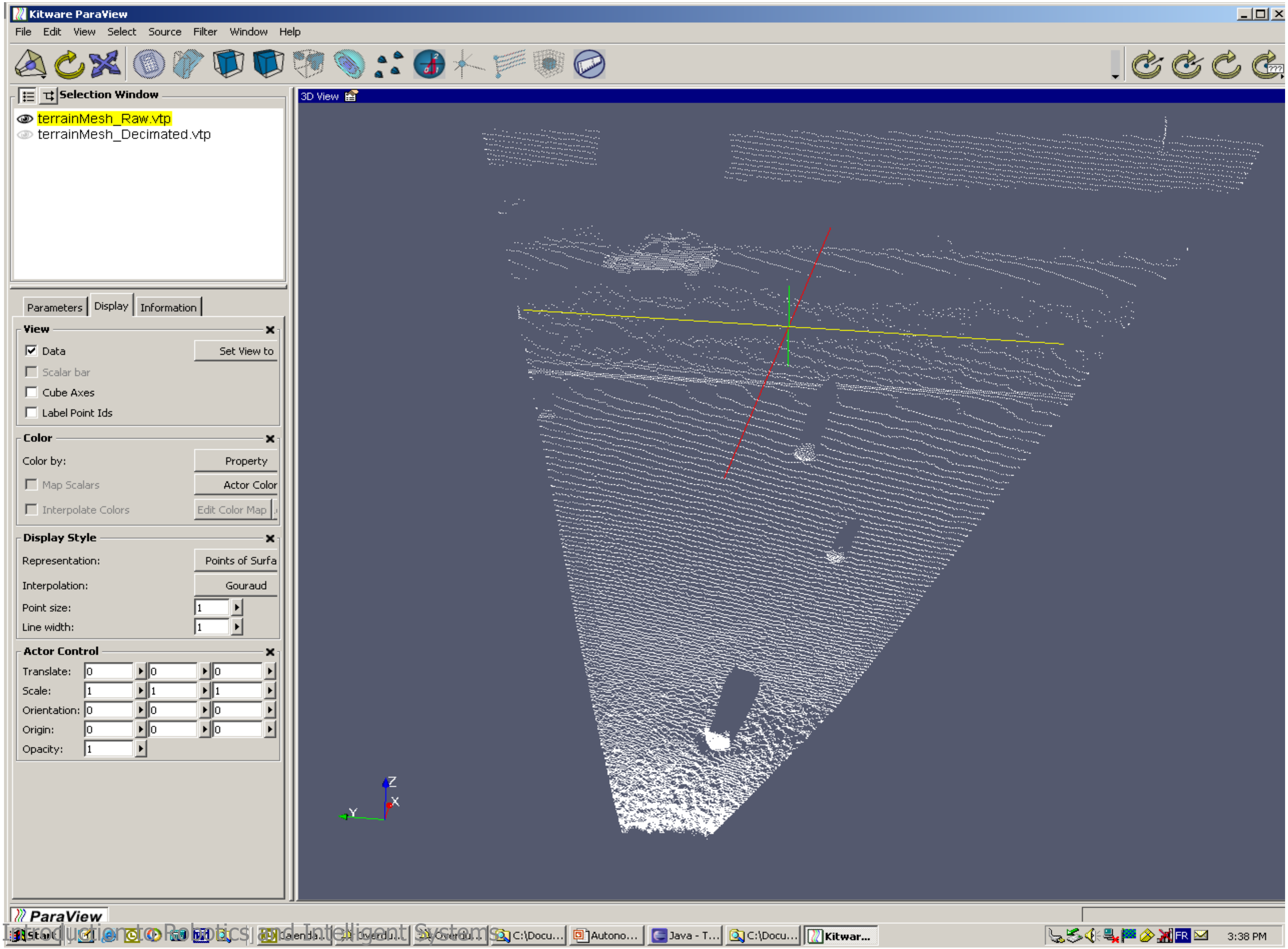


Simulated Scan

Delaunay Triangulation (Spherical Coordinates)
-Remove triangles from shadows (use 3D information)



Too far, classified as shadow



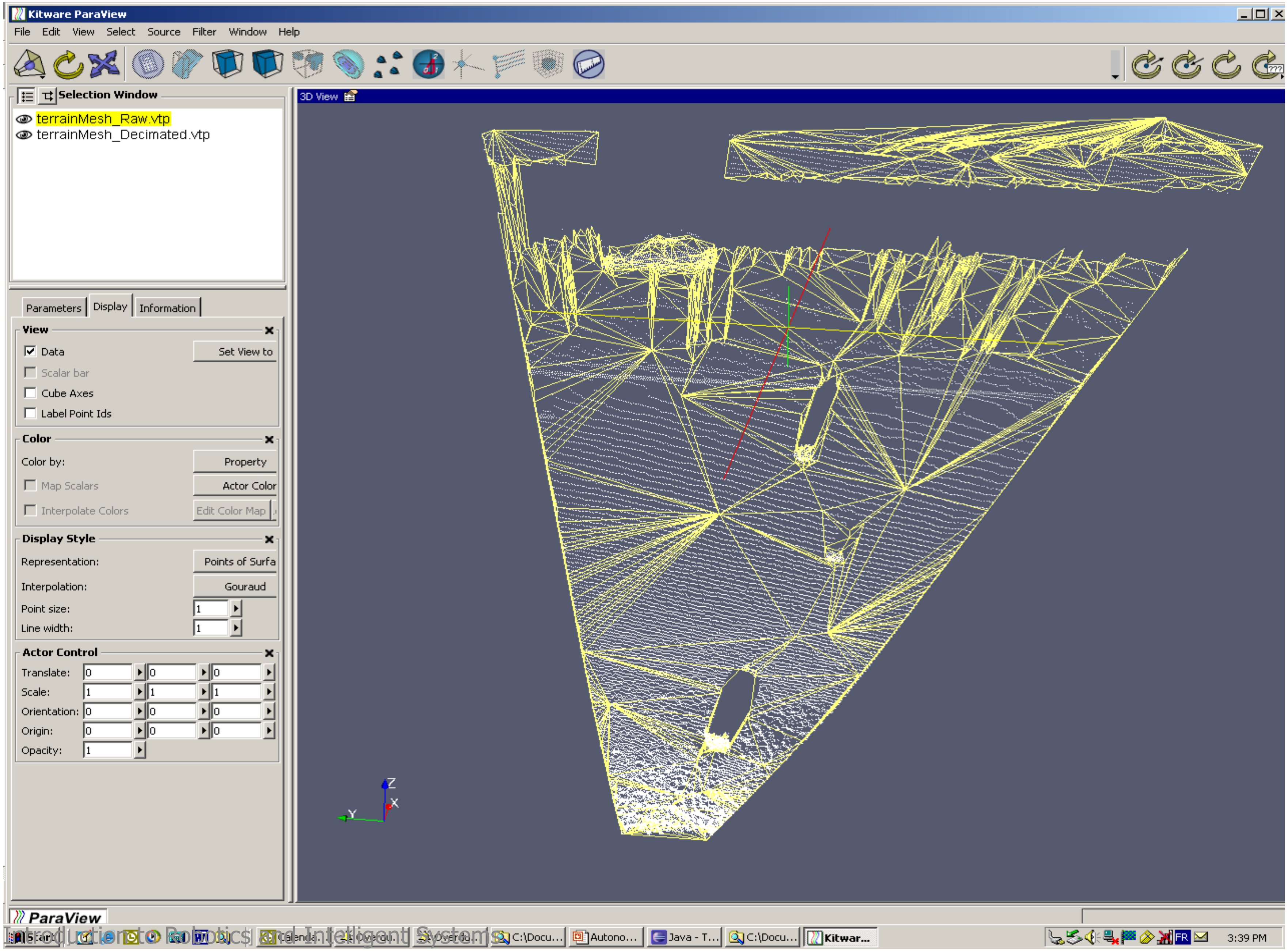
terrainMesh_Raw.vtp
terrainMesh_Decimated.vtp

☑ Data
☐ Scalar bar
☐ Cube Axes
☐ Label Point Ids

Color by: Property
☐ Map Scalars
☐ Interpolate Colors

Representation: Points of Surfa
Interpolation: Gouraud
Point size: 1
Line width: 1

Translate: 0 0 0
Scale: 1 1 1
Orientation: 0 0 0
Origin: 0 0 0
Opacity: 1



View

☑ Data — Set View to

☐ Scalar bar

☐ Cube Axes

☐ Label Point Ids

Color

Color by: Property

☐ Map Scalars — Actor Color

☐ Interpolate Colors — Edit Color Map

Display Style

Representation: Points of Surfa

Interpolation: Gouraud

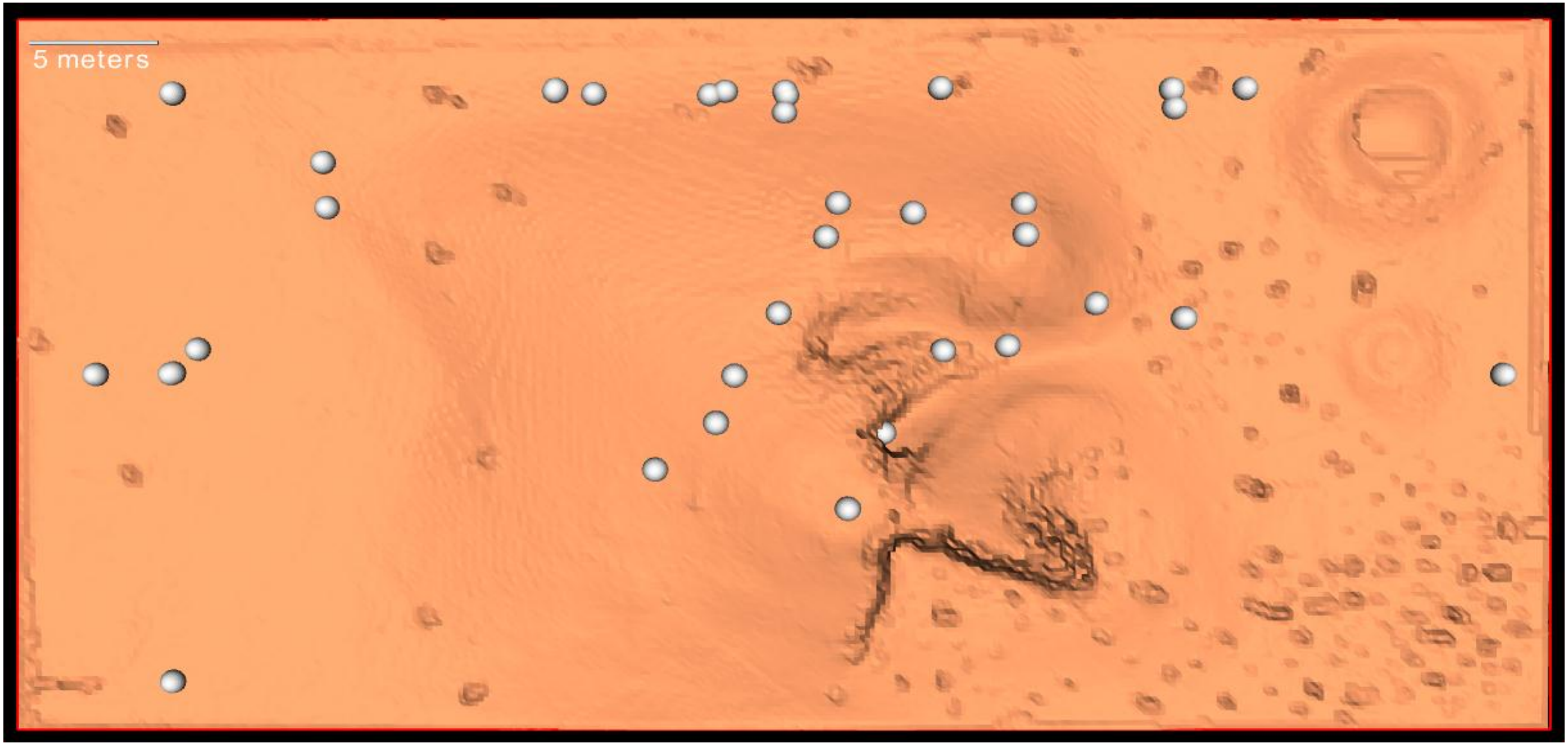
Point size: 1

Line width: 1

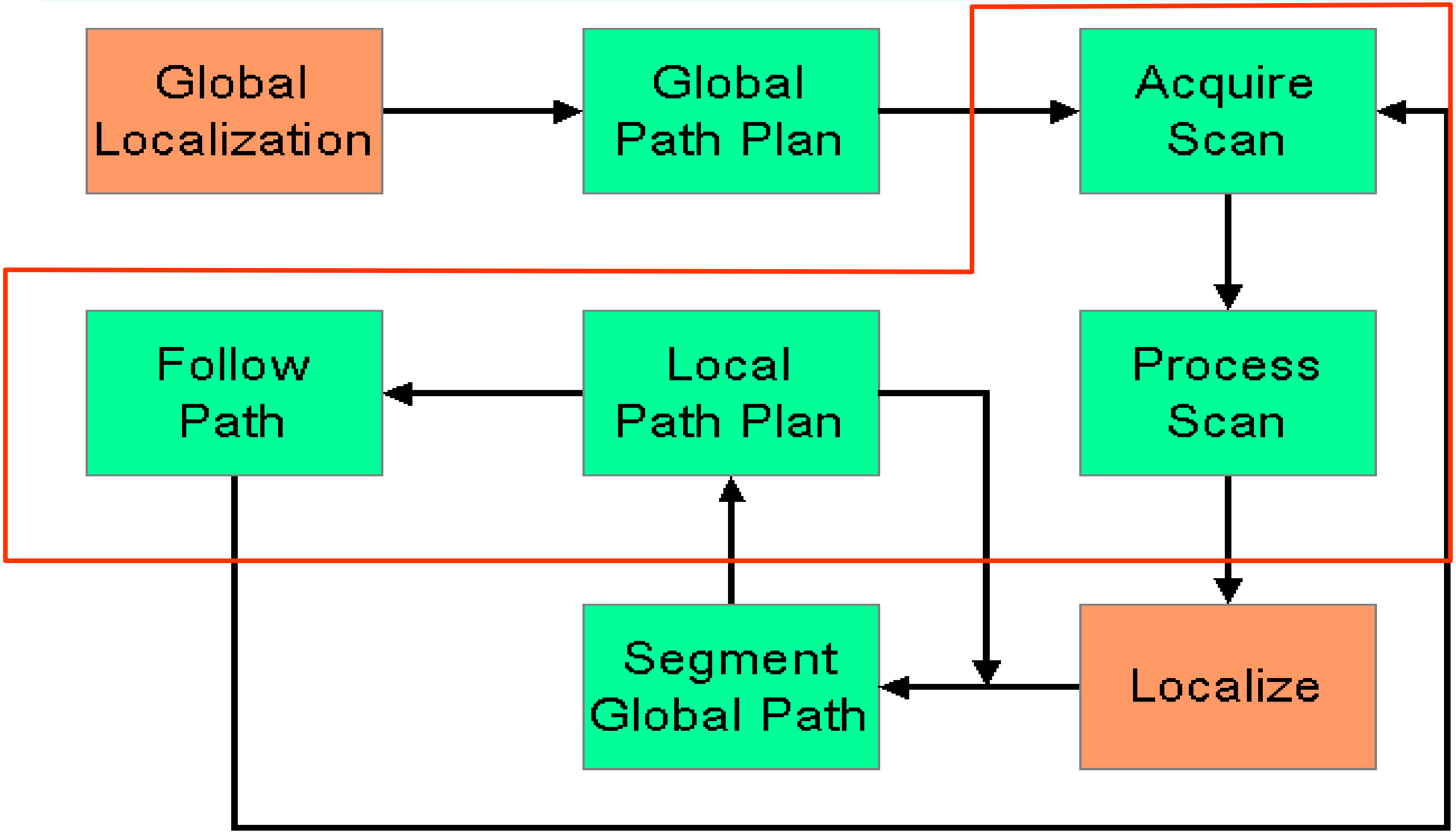
Actor Control

Translate:	0	0	0
Scale:	1	1	1
Orientation:	0	0	0
Origin:	0	0	0
Opacity:	1		

2006, Scans Collected: 96



2006, Over-the-Horizon Navigation

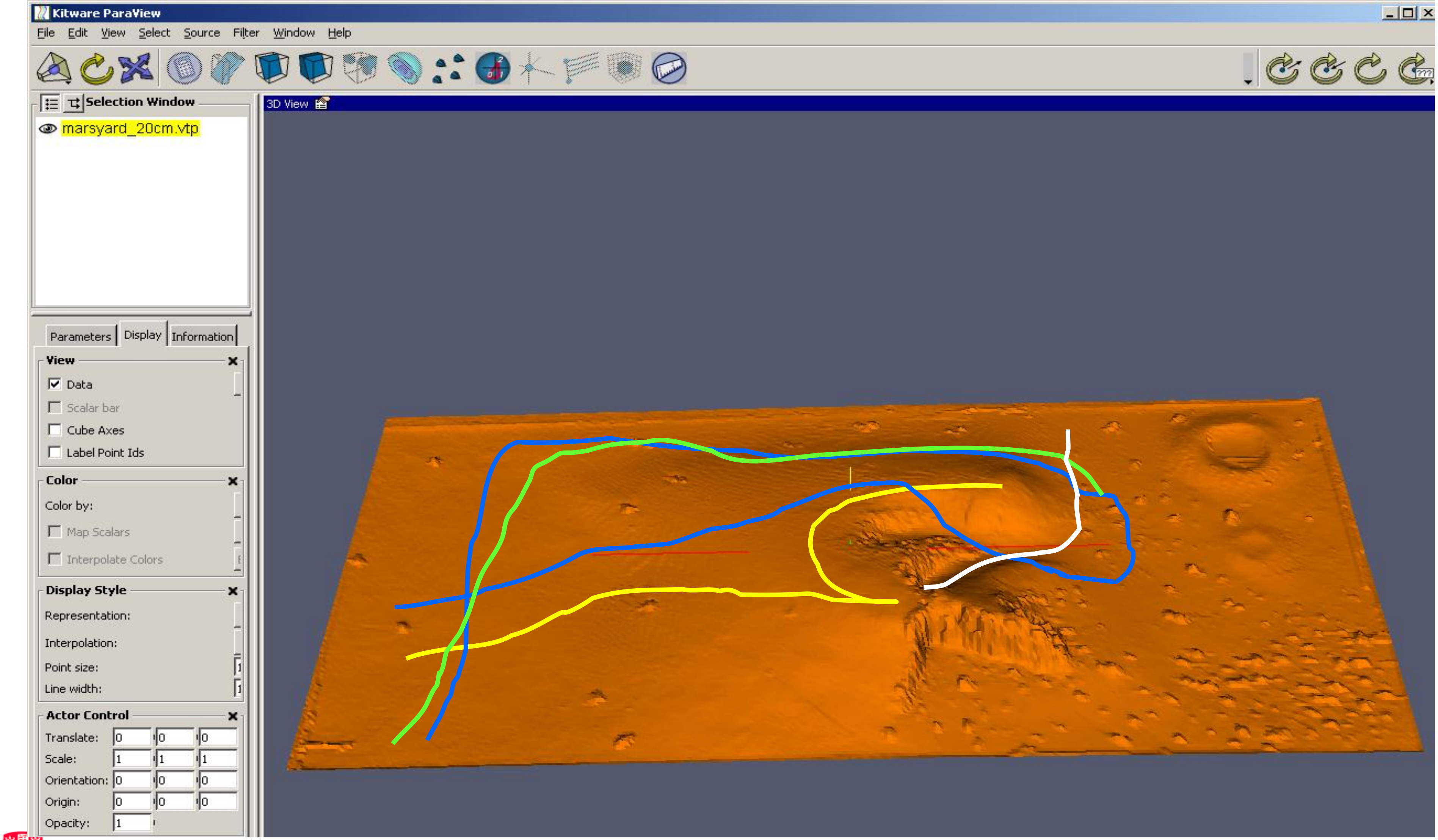


2006, Over-the-Horizon Traverses
Semi-Autonomous

- 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



marsyard_20cm.vtp

View

☑ Data

☐ Scalar bar

☐ Cube Axes

☐ Label Point Ids

Color

Color by:

☐ Map Scalars

☐ Interpolate Colors

Display Style

Representation:

Interpolation:

Point size:

Line width:

Actor Control

Translate: 0 0 0

Scale: 1 1 1

Orientation: 0 0 0

Origin: 0 0 0

Opacity: 1

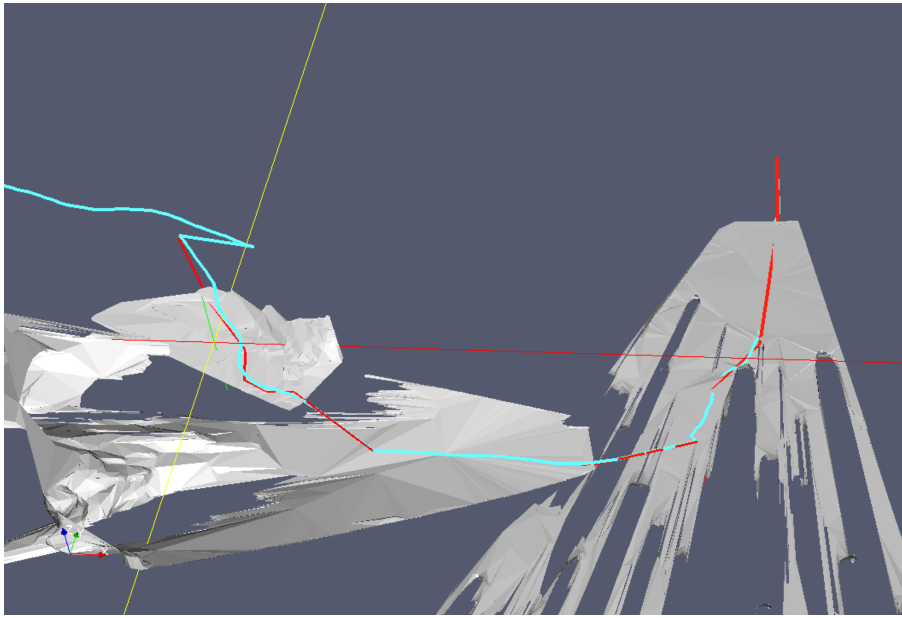
Lessons Learned from 2006 Testing Period

- 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



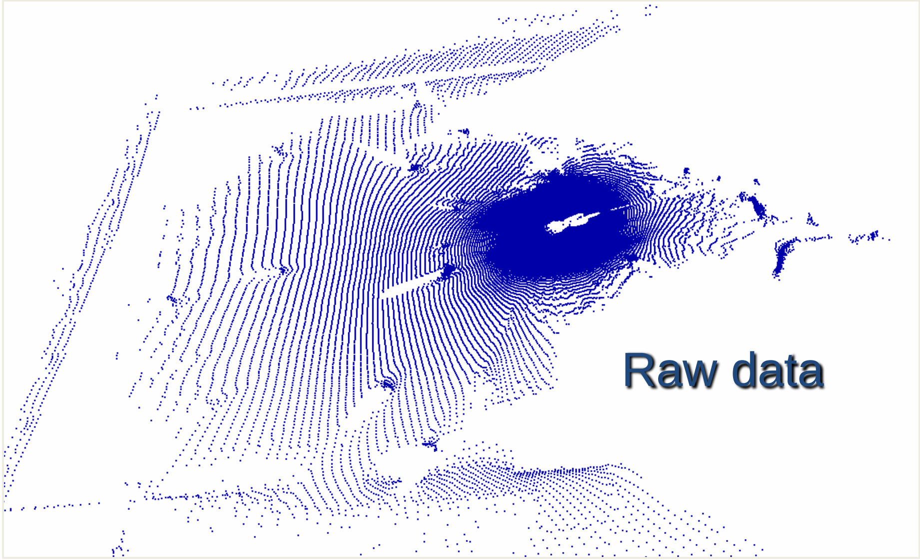
- Top level issues:
  - Environment Sensor Unwieldy
    - FOV Too Narrow
    - Logistics a Nightmare
  - Horizon Sometimes Much Closer than Expected
  - Environment Scans Need to be Interpreted (Shadows)

2007 Test Campaign

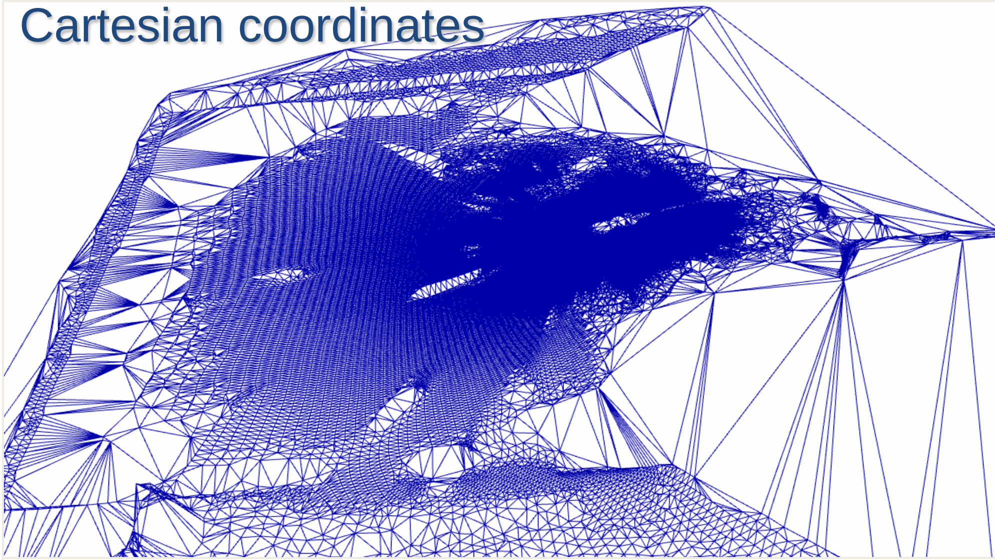
Updates in the Testbed 2007

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

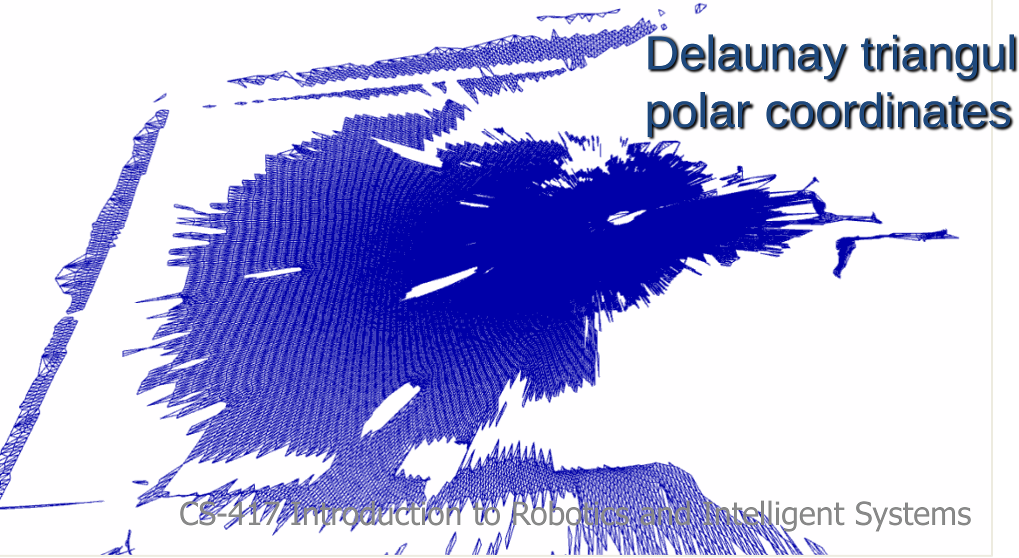
Scan Processing



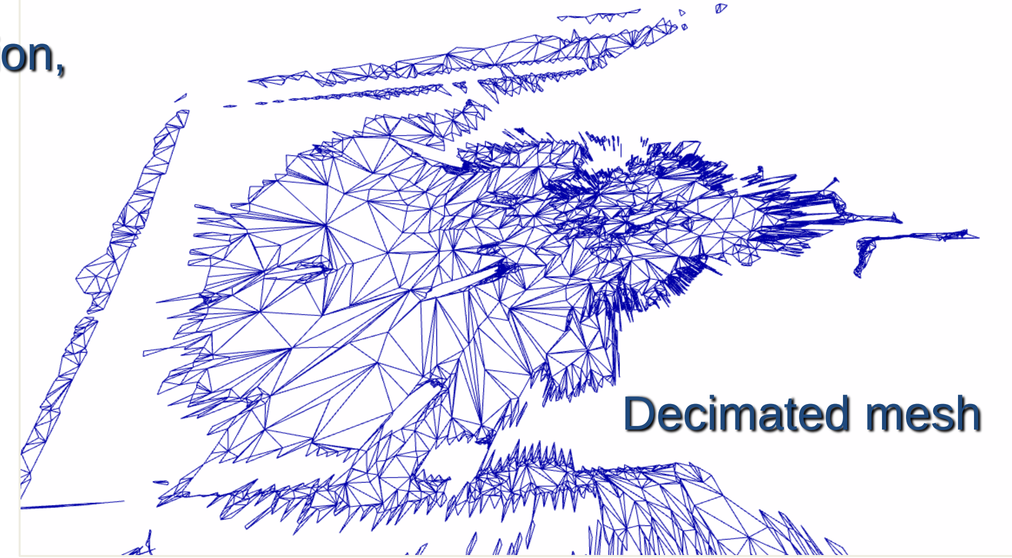
Raw data



Delaunay triangulation, Cartesian coordinates

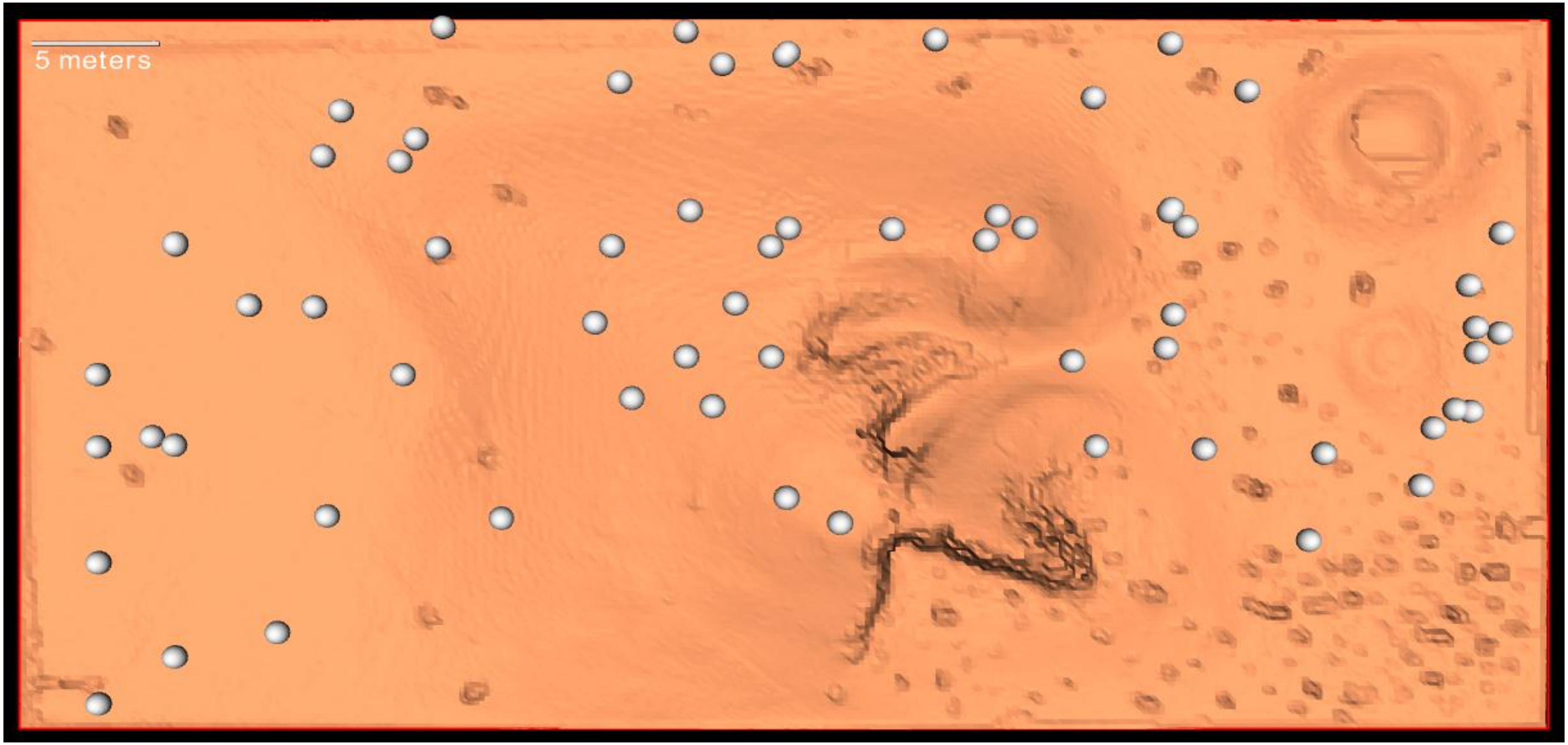


Delaunay triangulation, polar coordinates



Decimated mesh

2007, Scans Collected: 93



Comparison between the two LIDARs

SICK on Pan Unit

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

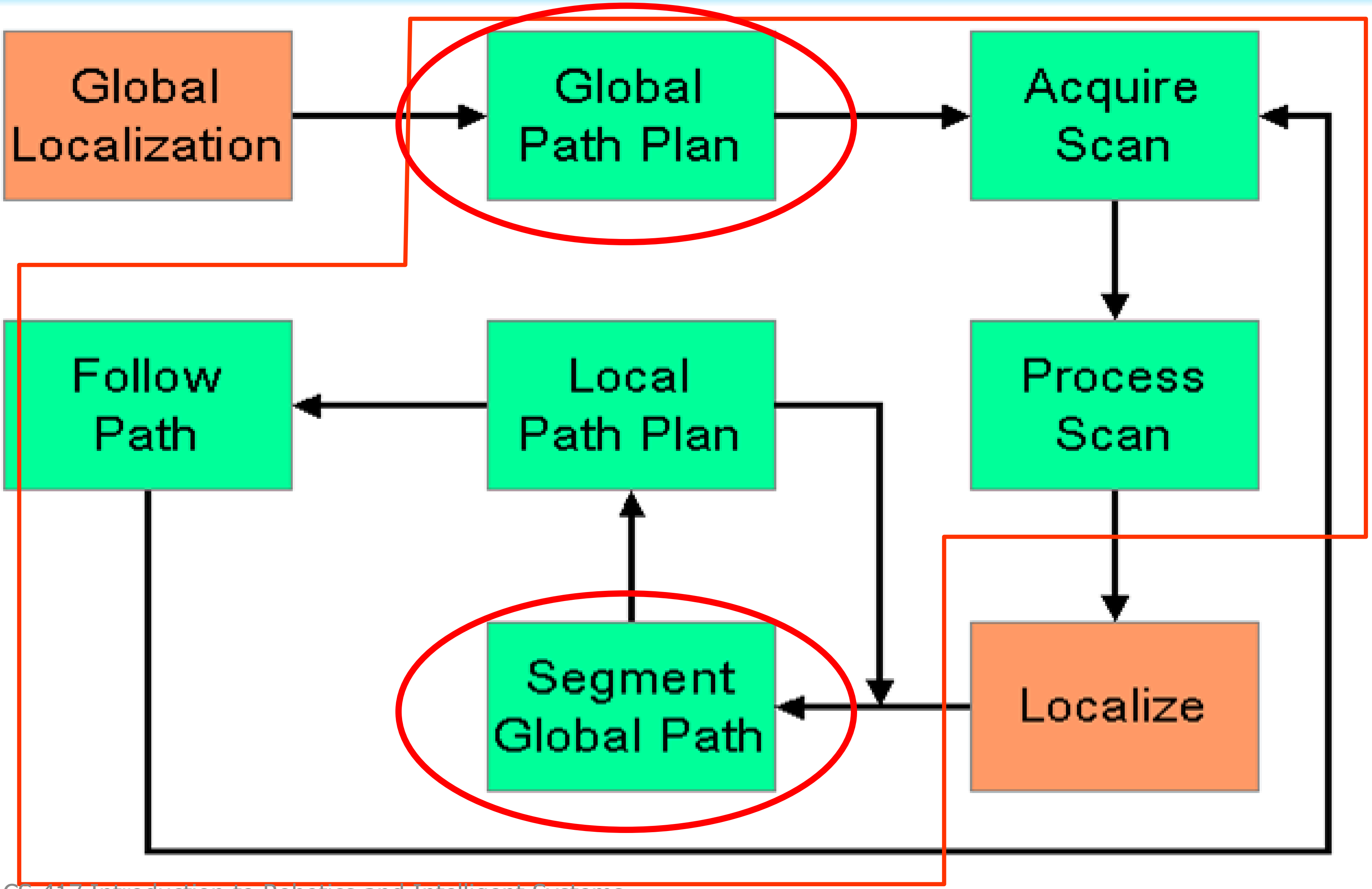
ILRIS 3D

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

Irregular Triangular Mesh Decimation

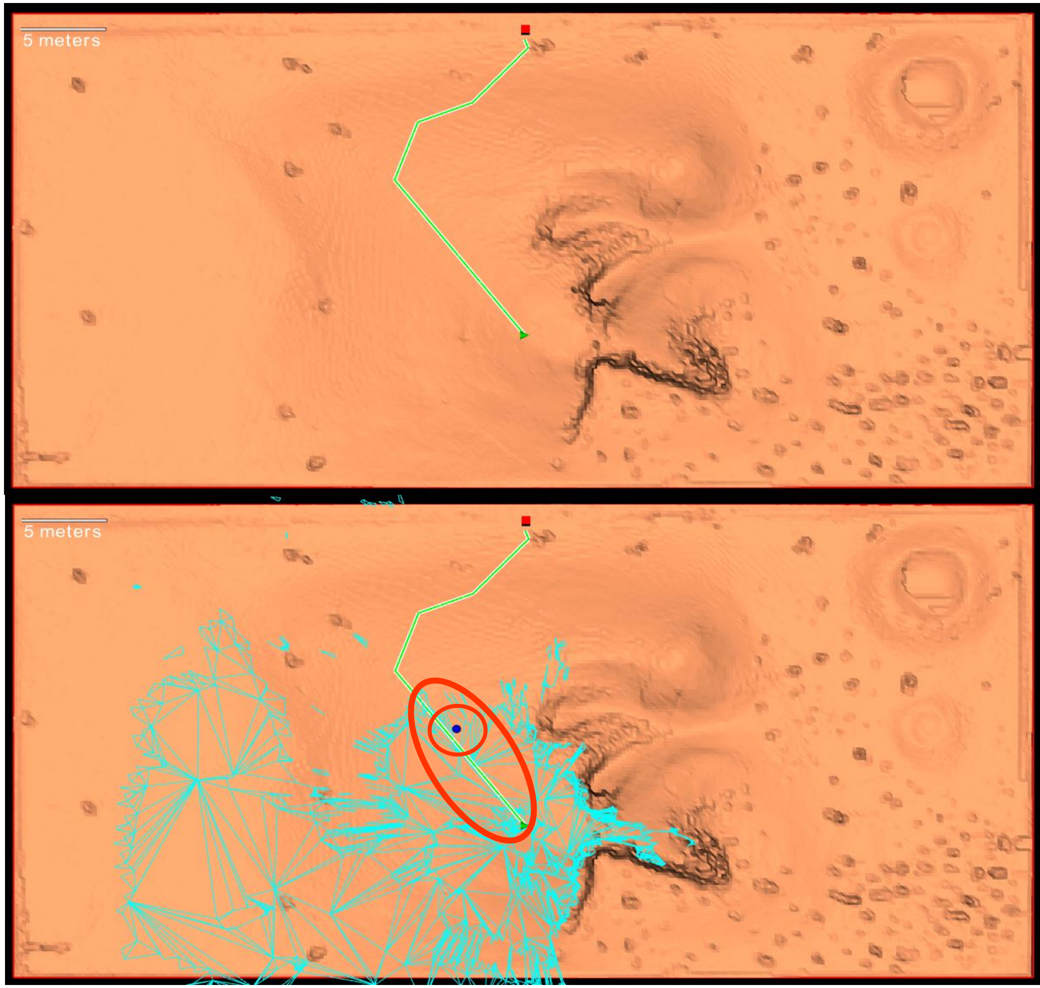
				Target Decimation Ratio					
				80%		90%		95%	
2006	**Points (mean)**	**31200**	6530	79.00%	3440	88.86%	2090	93.09%	
	Triangles (mean)	**61700**	12300	80.00%	6190	89.91%	3590	94.01%	
2007	**Points (mean)**	**111000**	23400	78.91%	12500	88.72%	6700	93.69%	
	Triangles (mean)	**216000**	43300	80.00%	21600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

2007, Over-the-Horizon Navigation



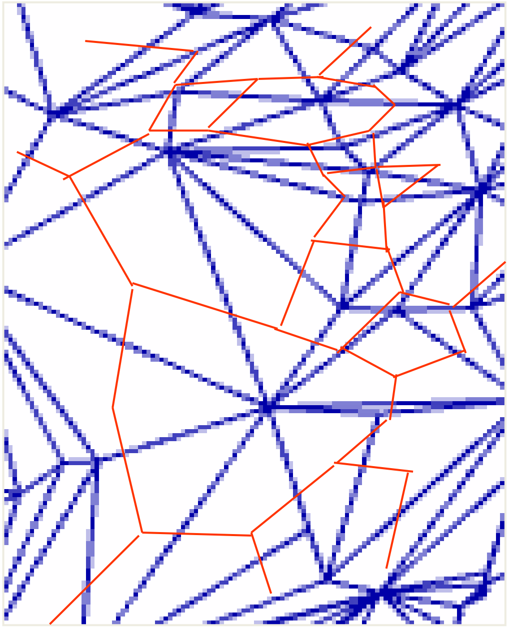
Global Path Plan and Segmentation

- 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



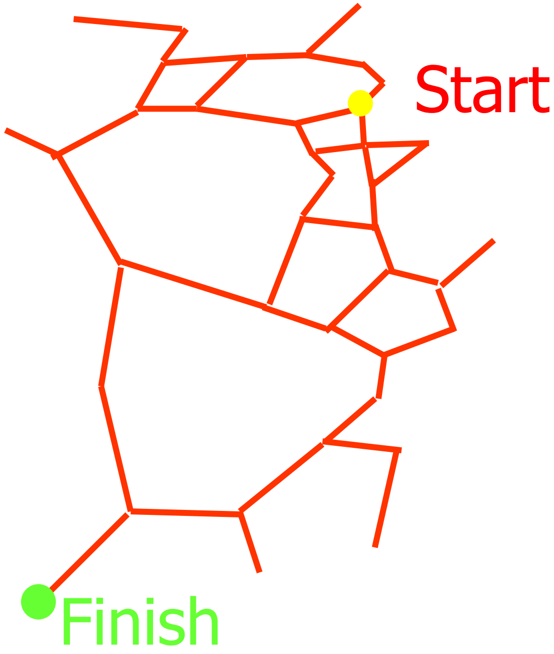
Path Planning

- Convert ITM into Connected Graph



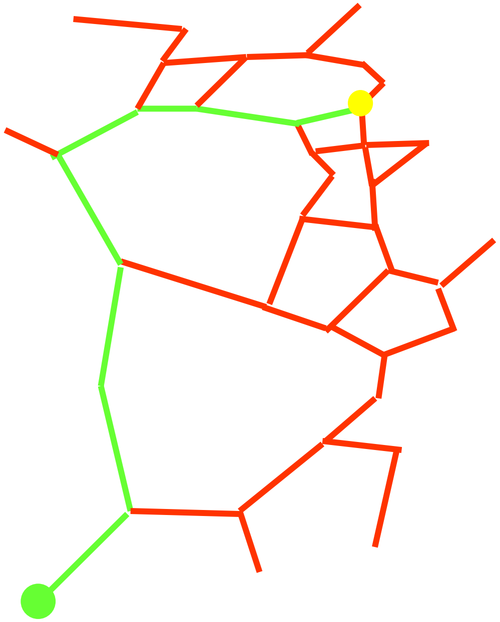
Path Planning

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



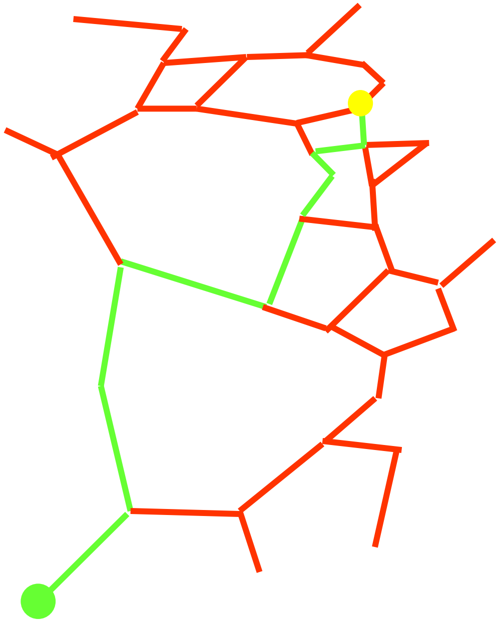
Planning

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



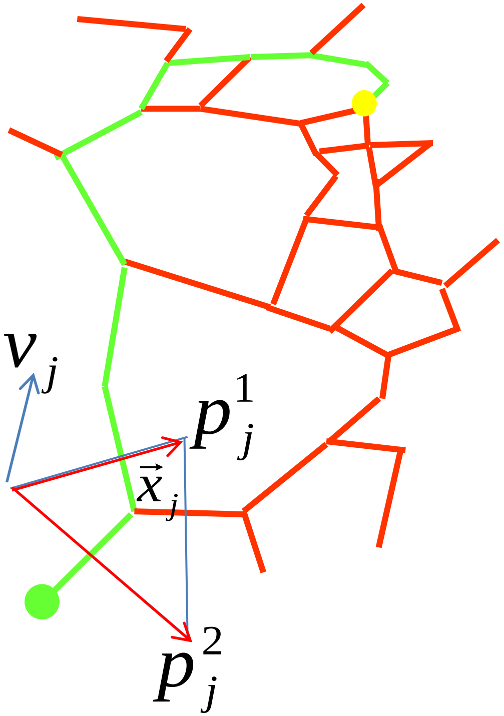
Planning

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



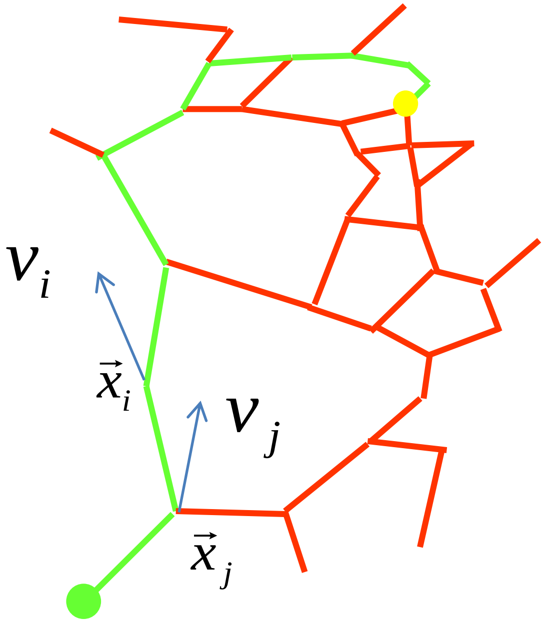
Planning

- 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



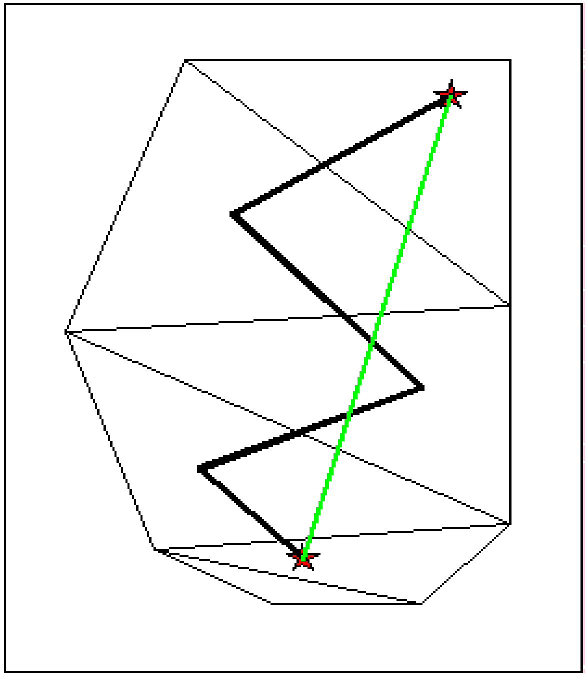
Path Planning

- 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

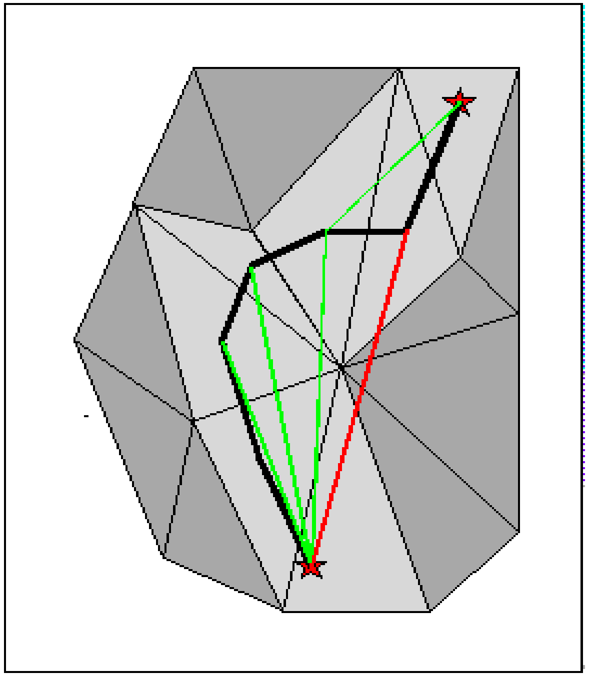
- Path Simplification

  Point-Robot

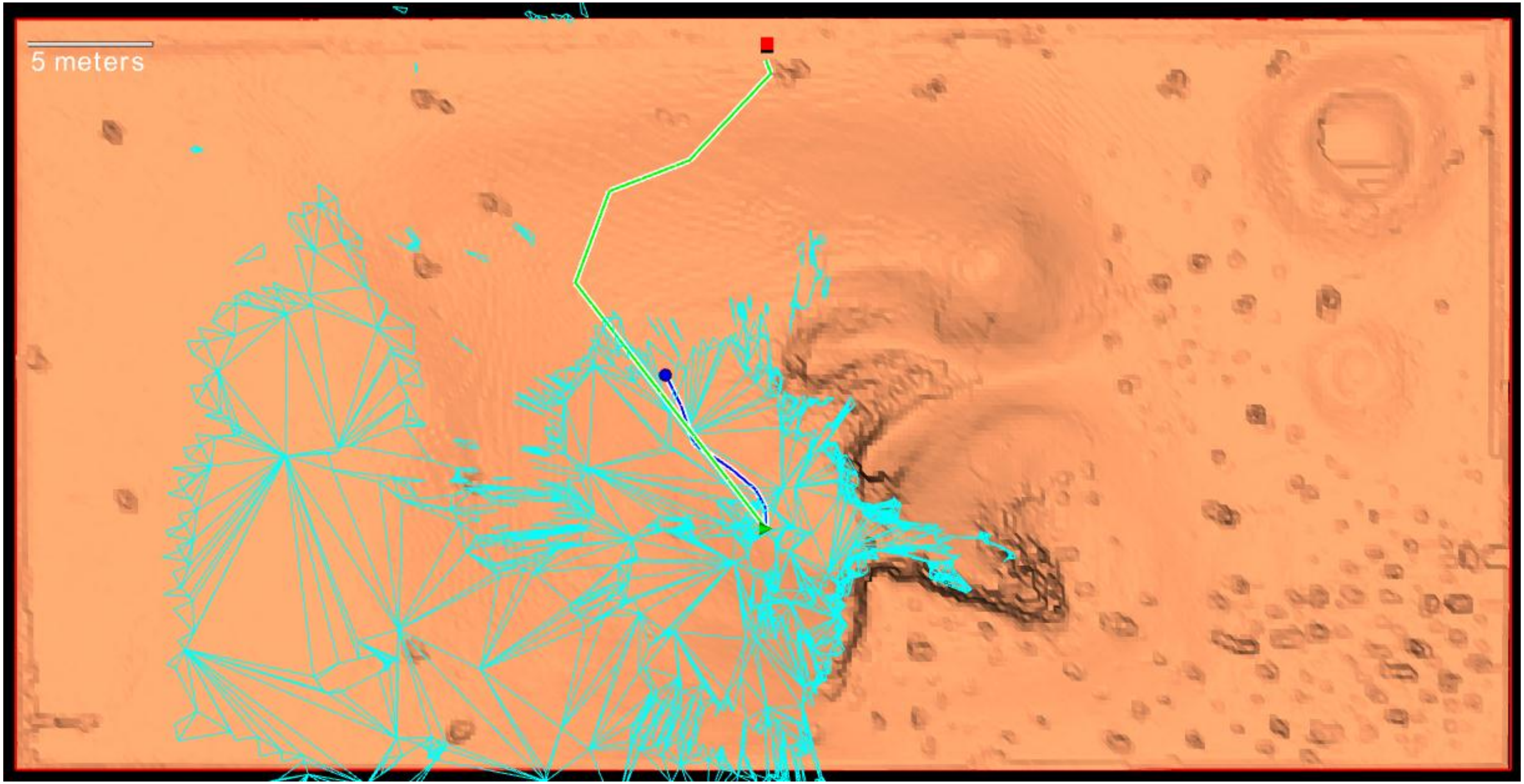


- Path Simplification

  Safety Corridor



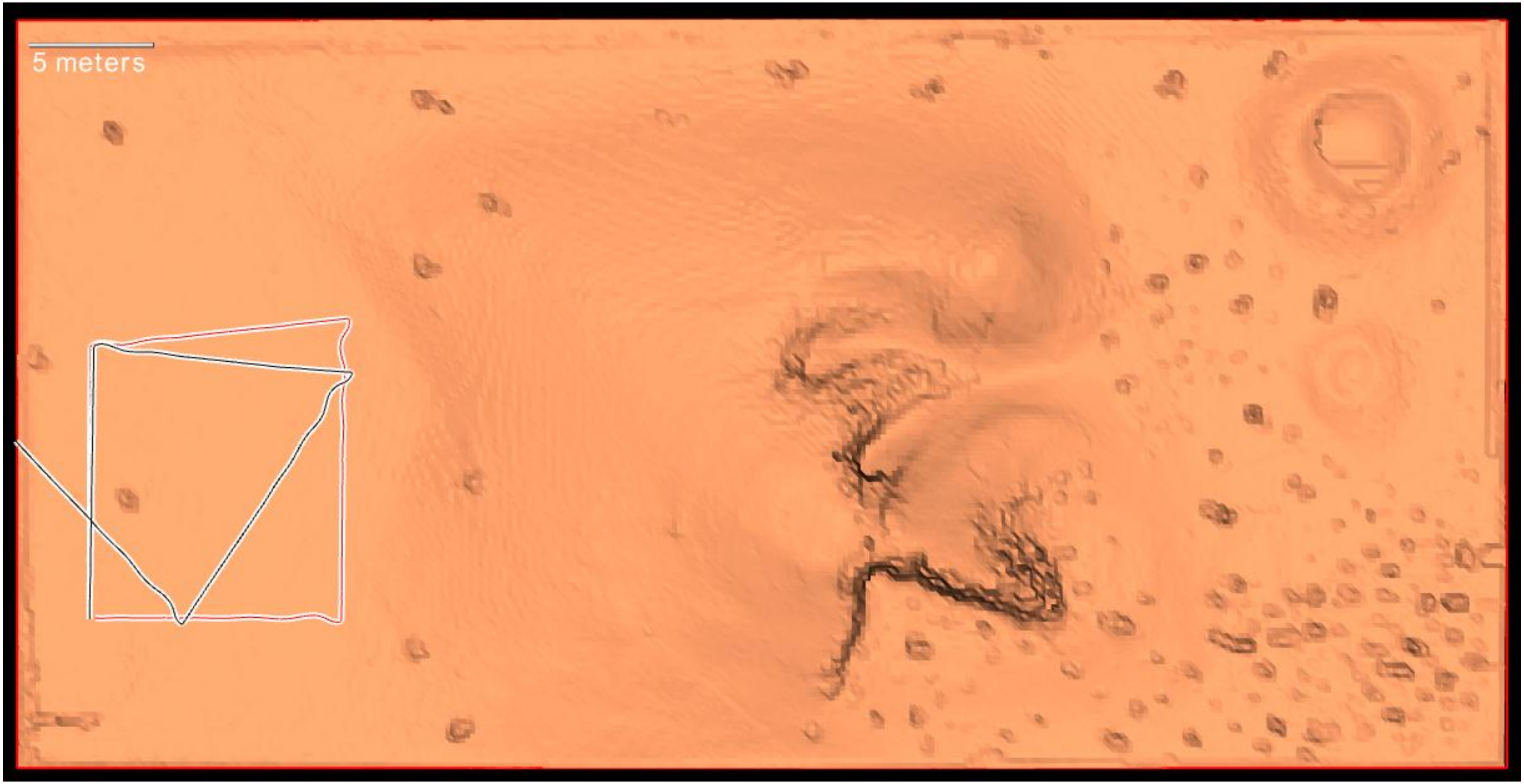
Local Path Plan



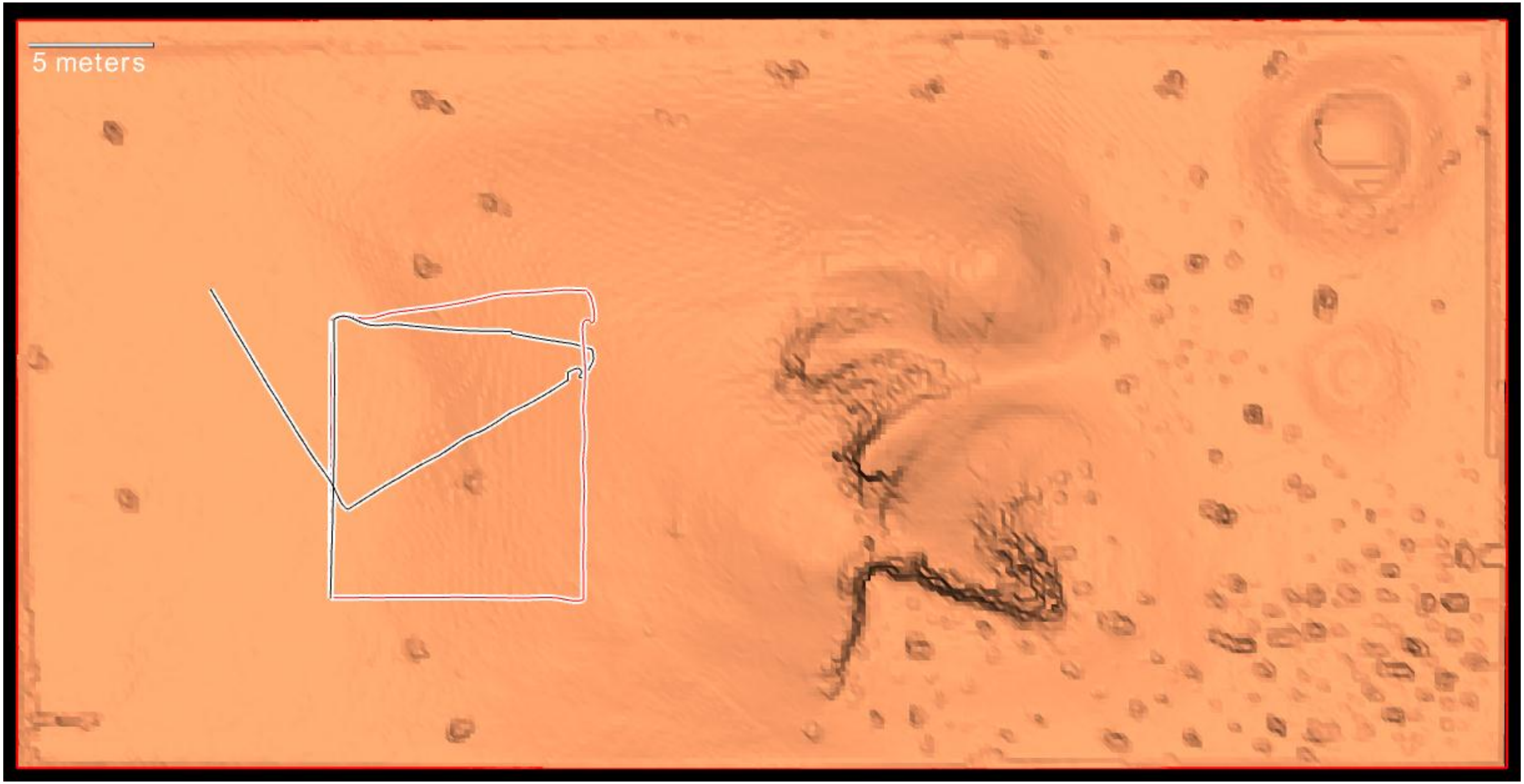
Motion Control

- 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

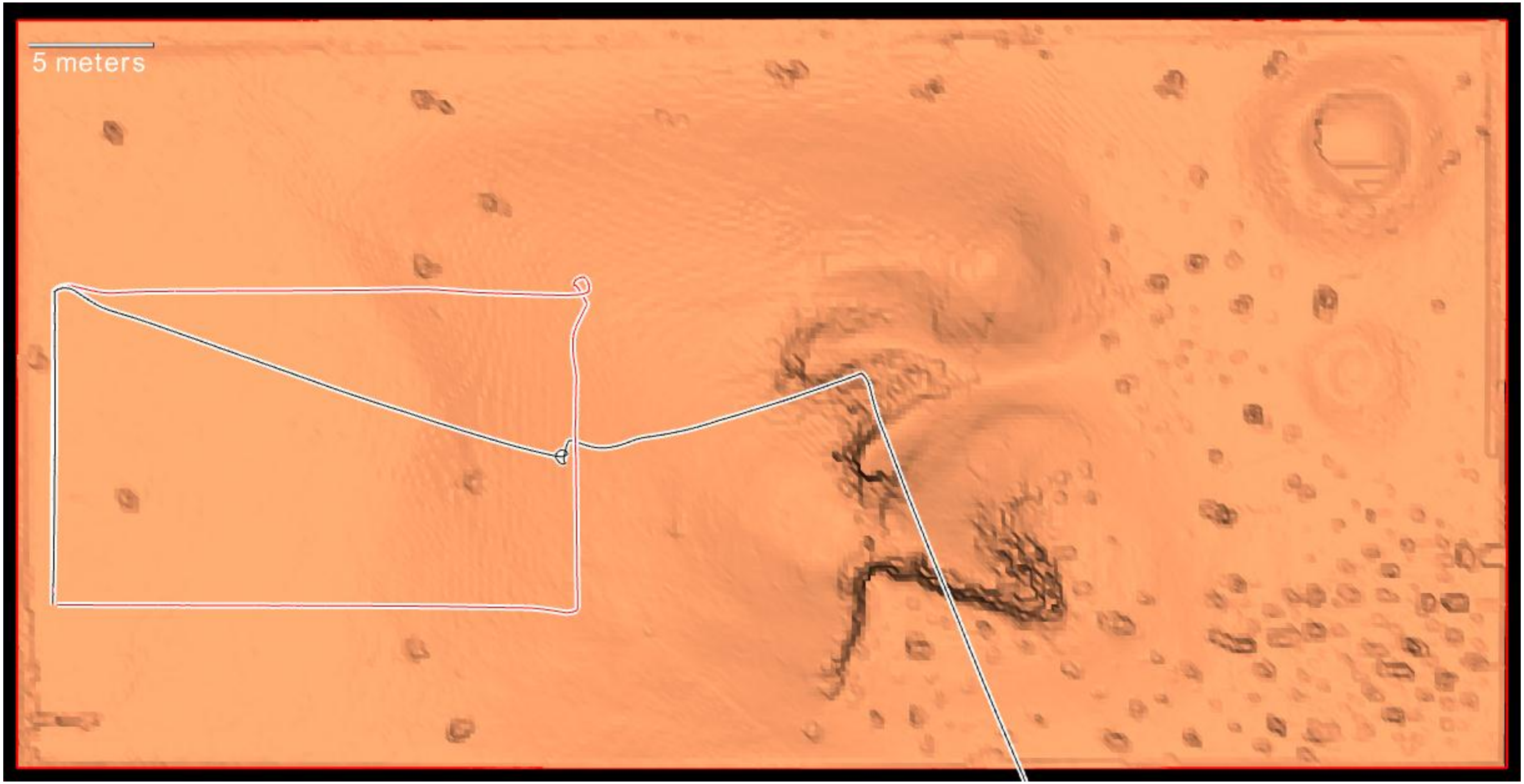
Closed Loop Tests



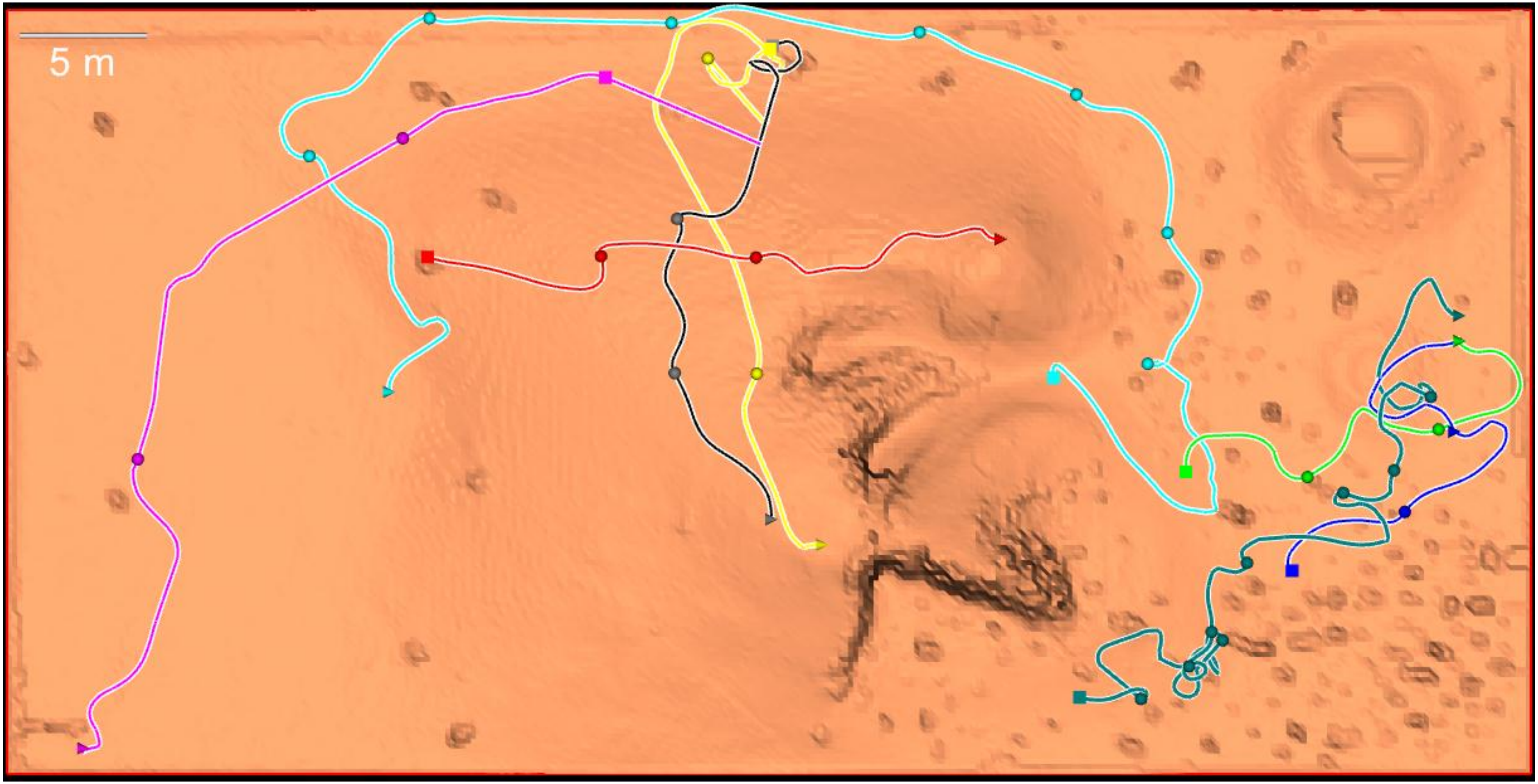
Closed Loop Tests



Closed Loop Tests



The Mars Terrain and Trajectories

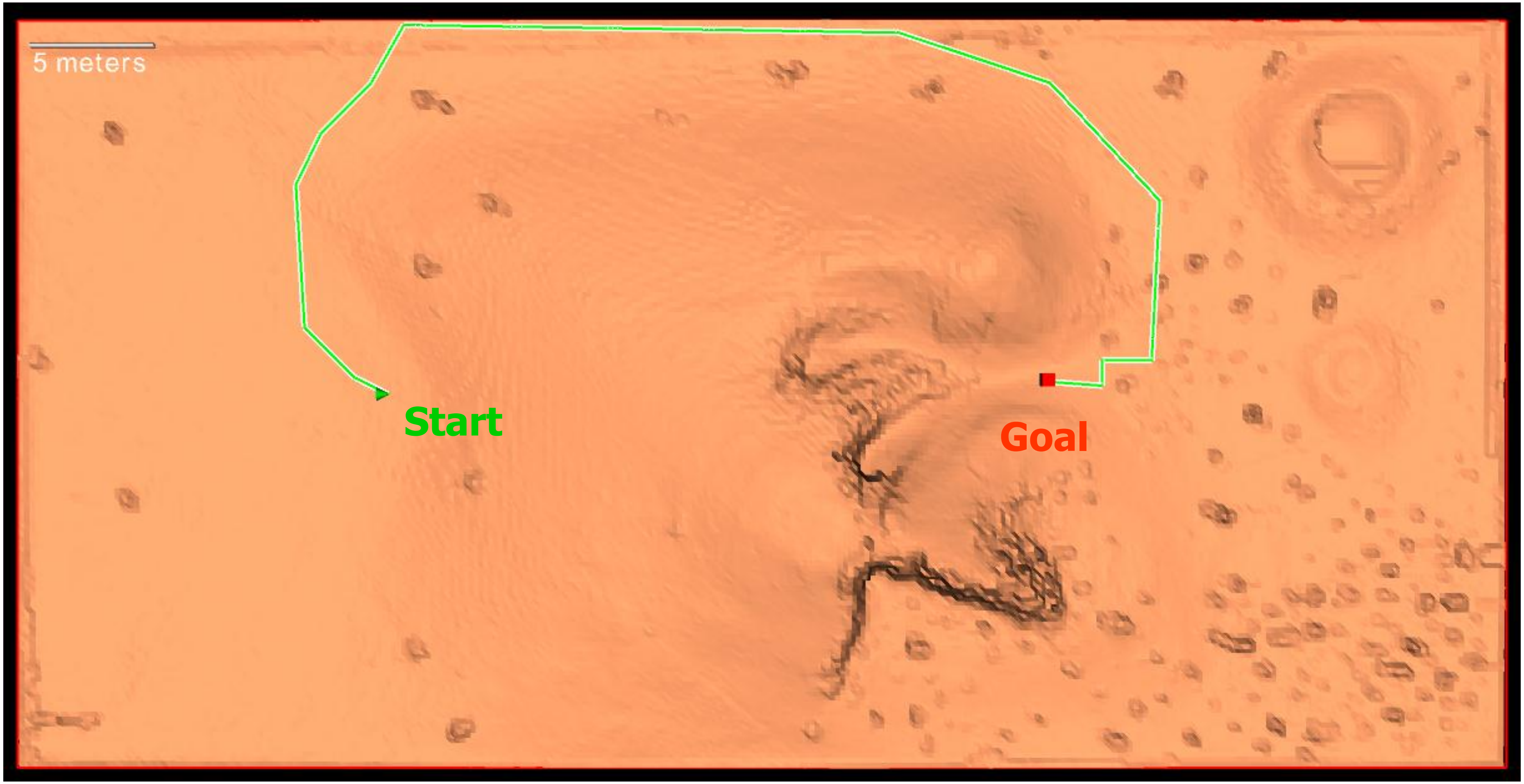


30 m

60 m

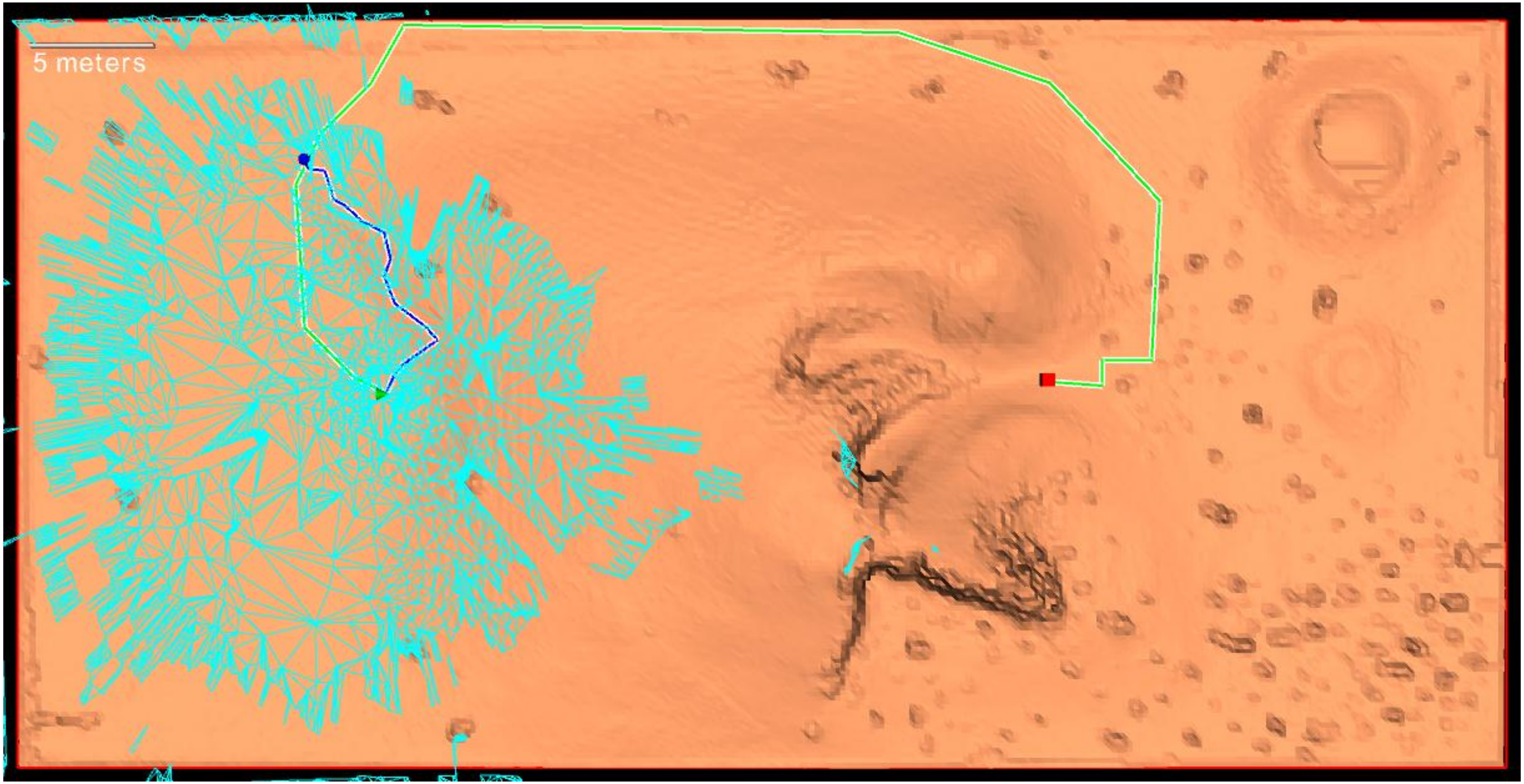
Fully Autonomous Navigation

from flat to canyon



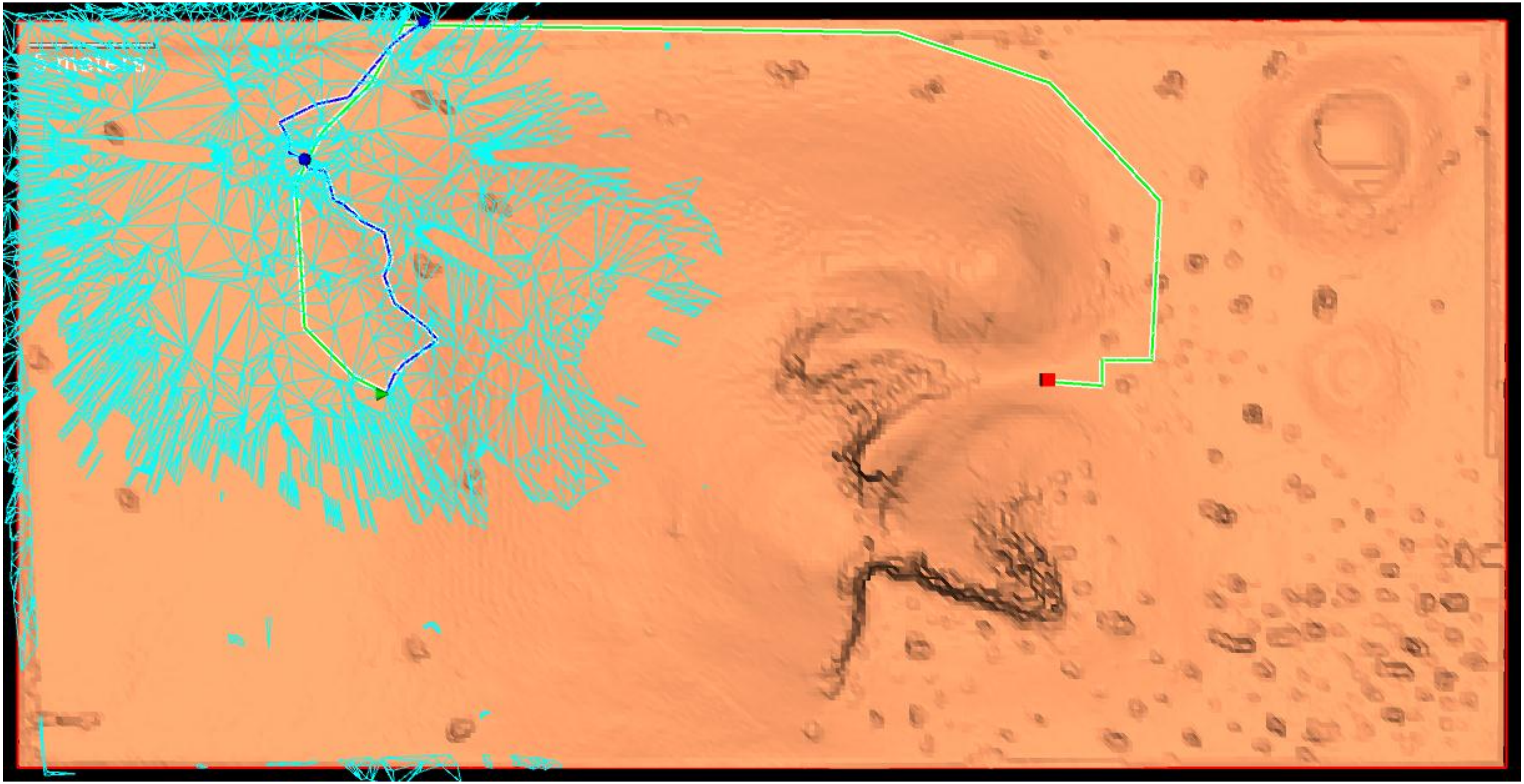
Fully Autonomous Navigation

from flat to canyon



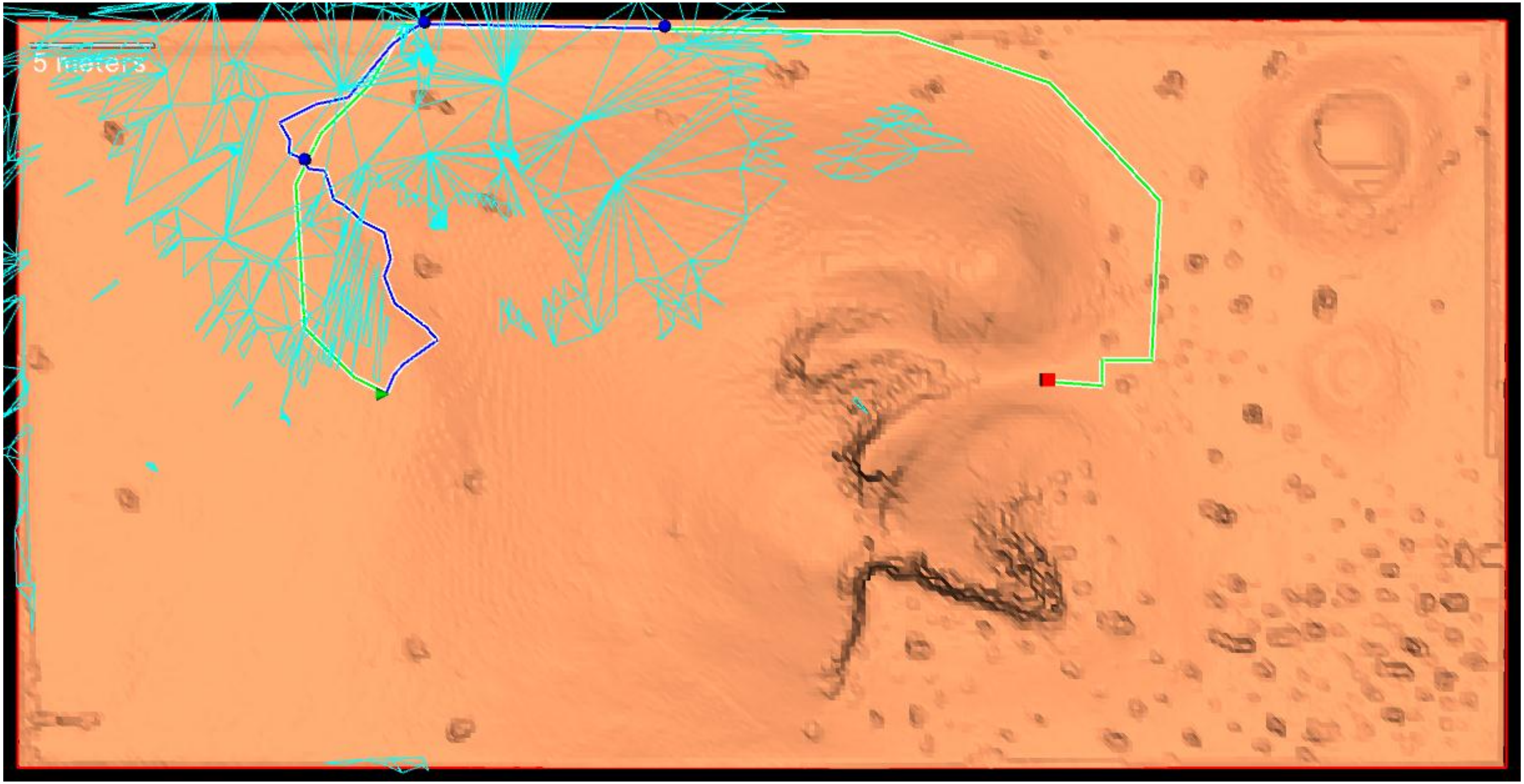
Fully Autonomous Navigation

from flat to canyon



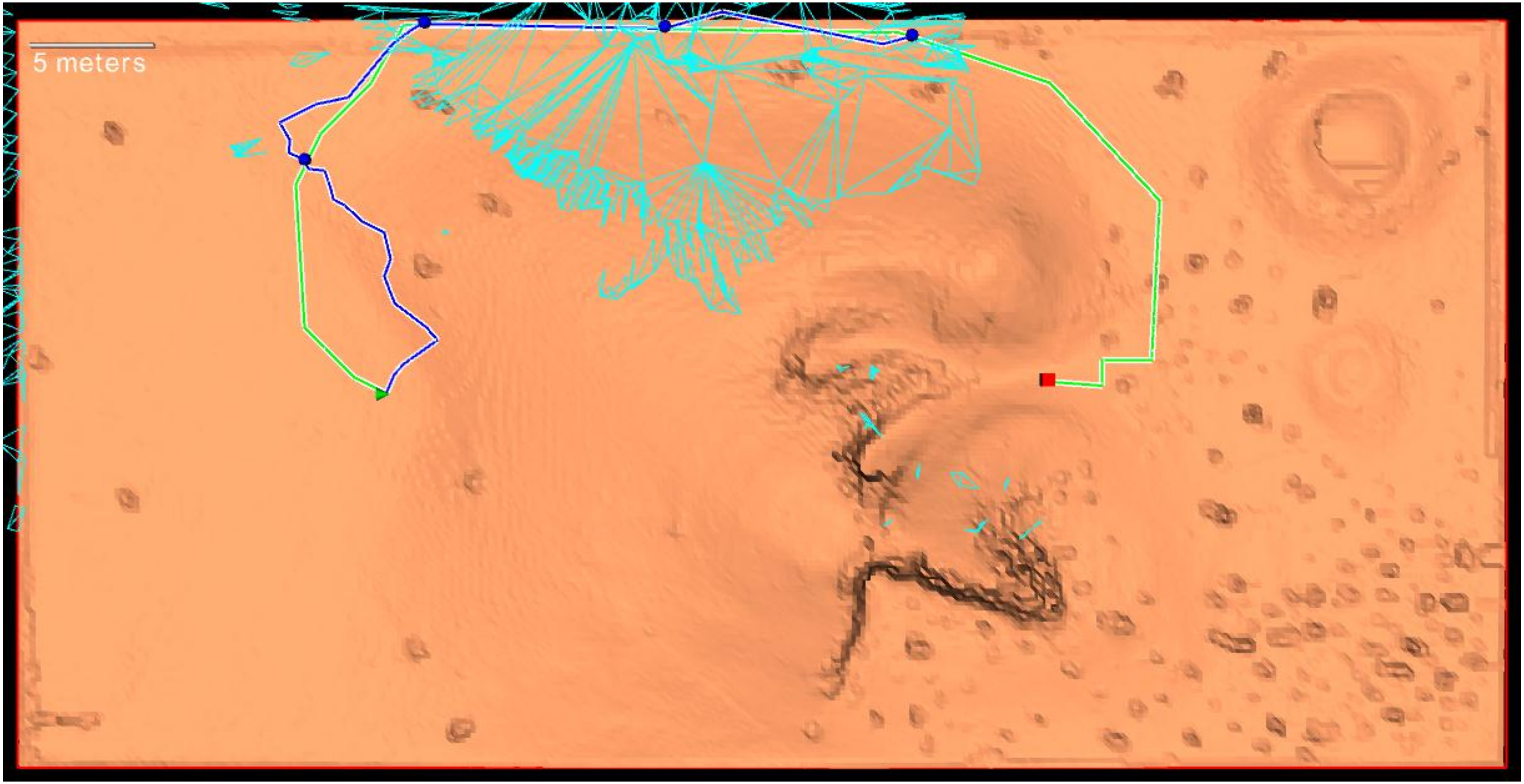
Fully Autonomous Navigation

from flat to canyon

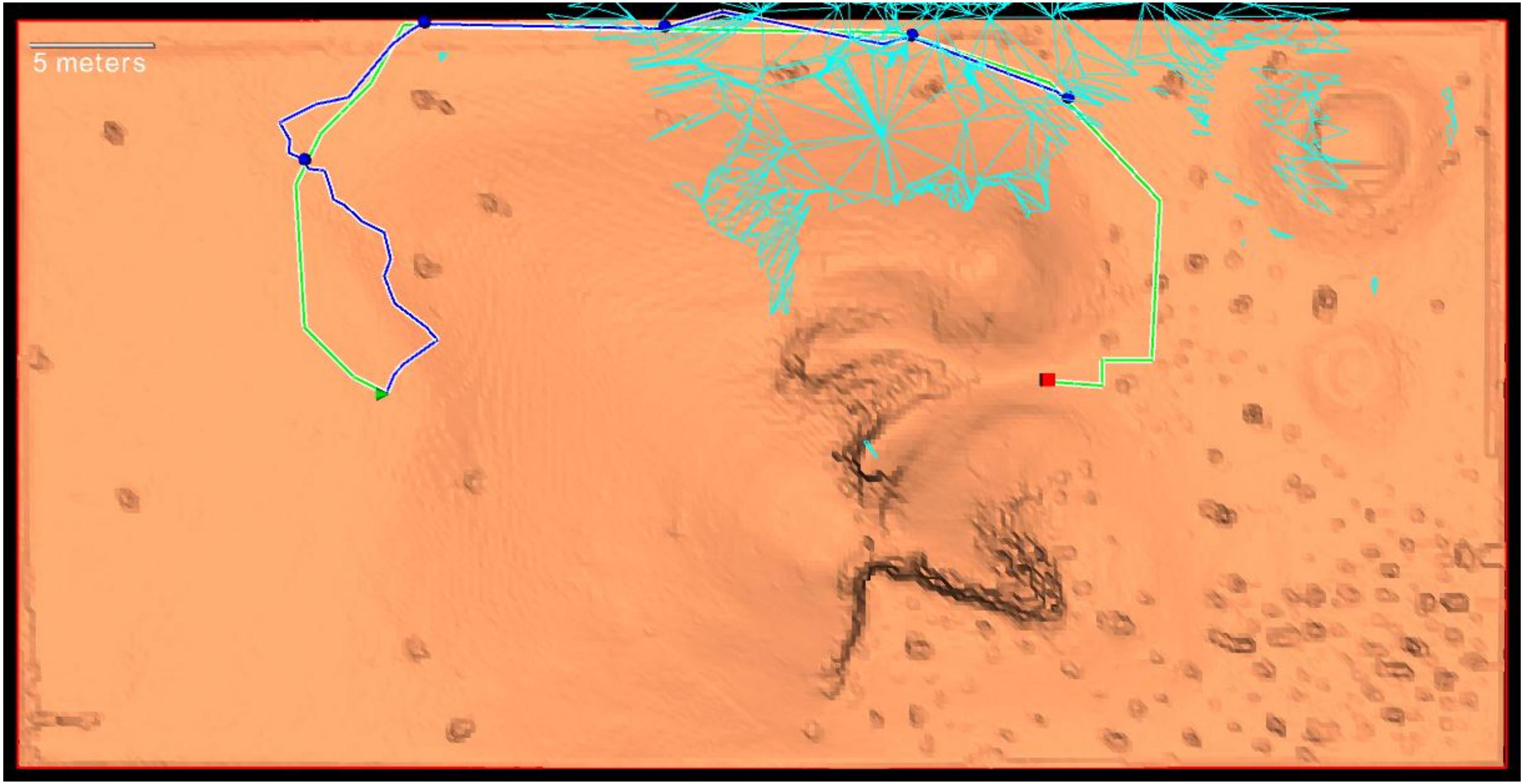


Fully Autonomous Navigation

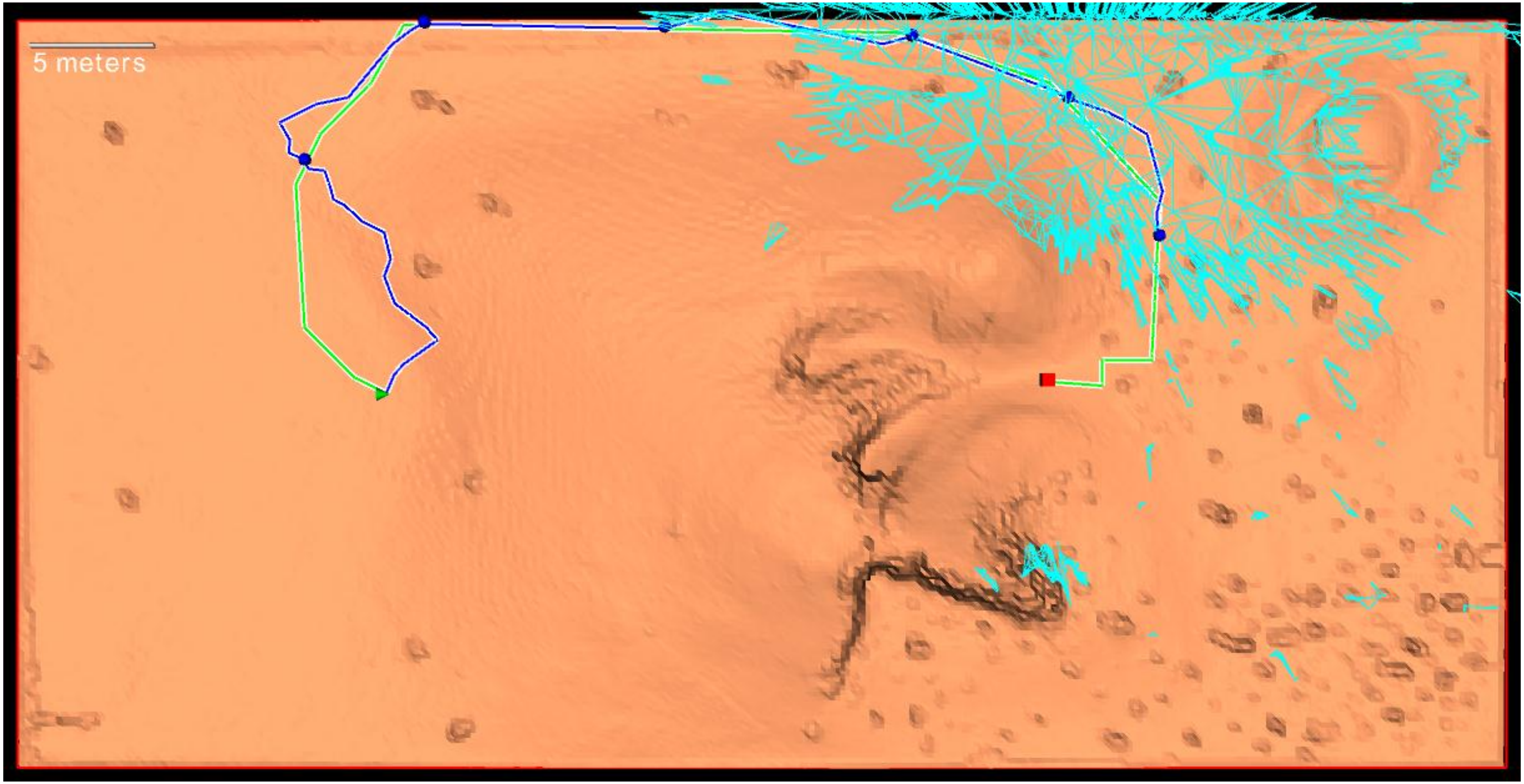
from flat to canyon



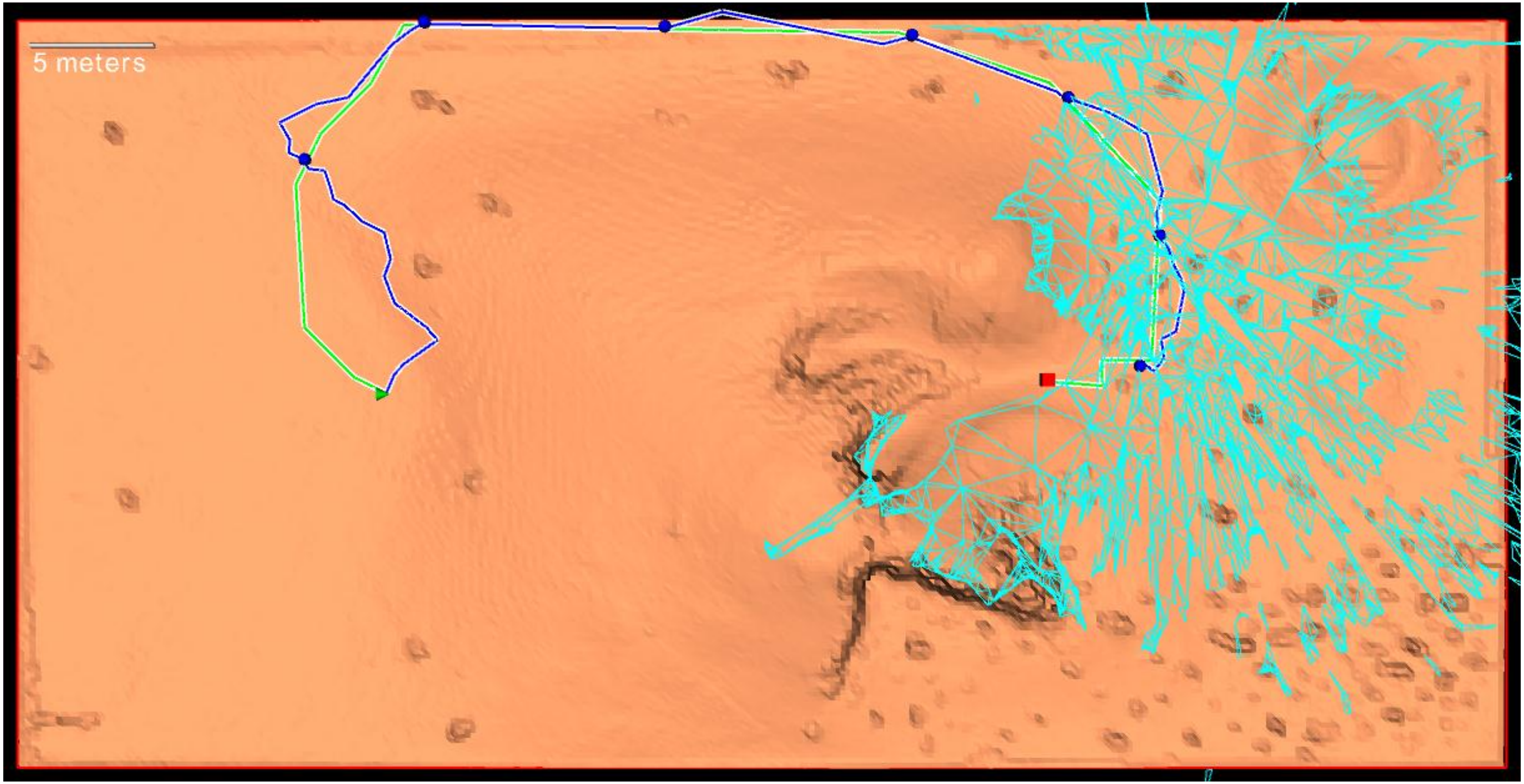
Fully Autonomous Navigation
from flat to canyon



Fully Autonomous Navigation
from flat to canyon

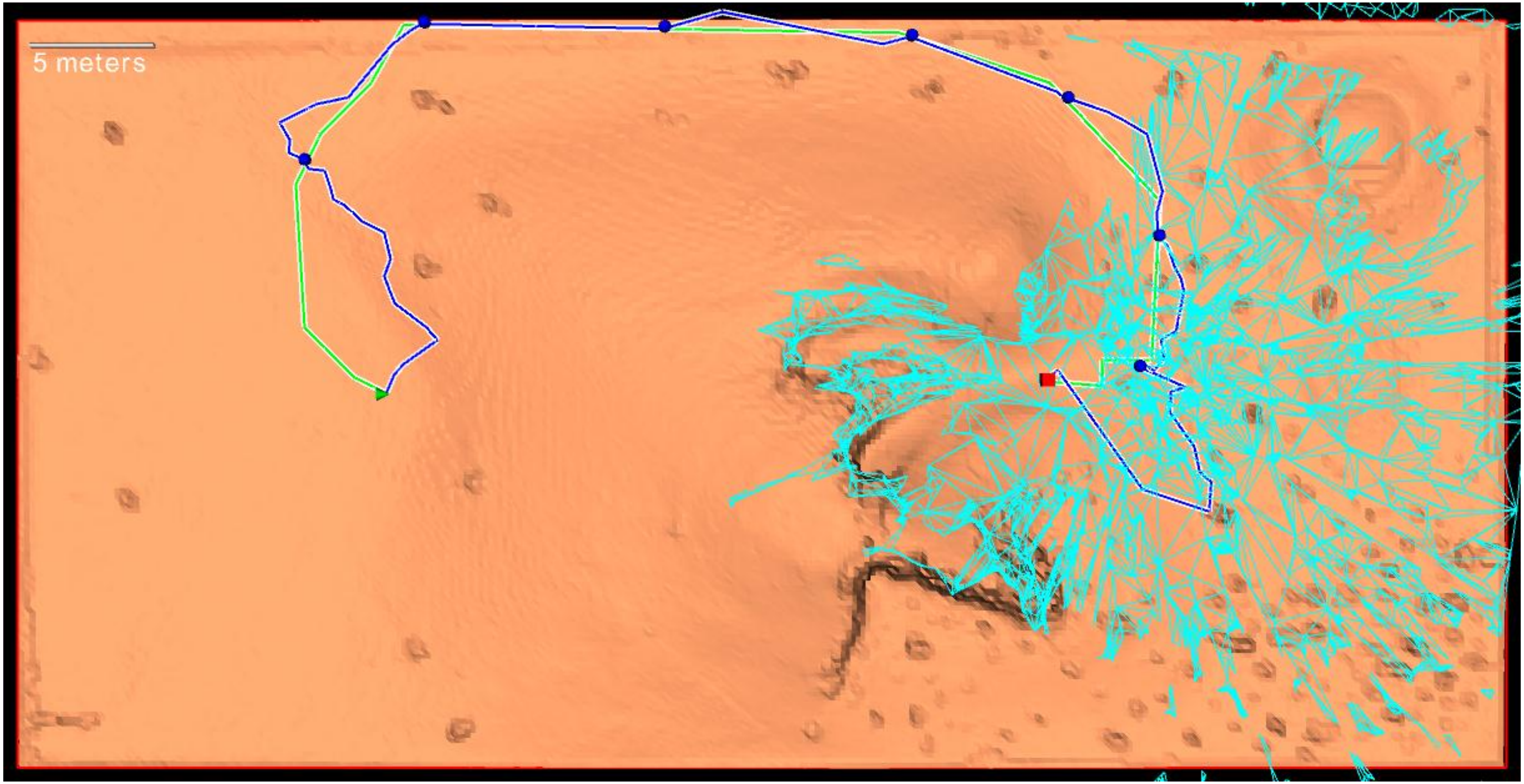


Fully Autonomous Navigation
from flat to canyon

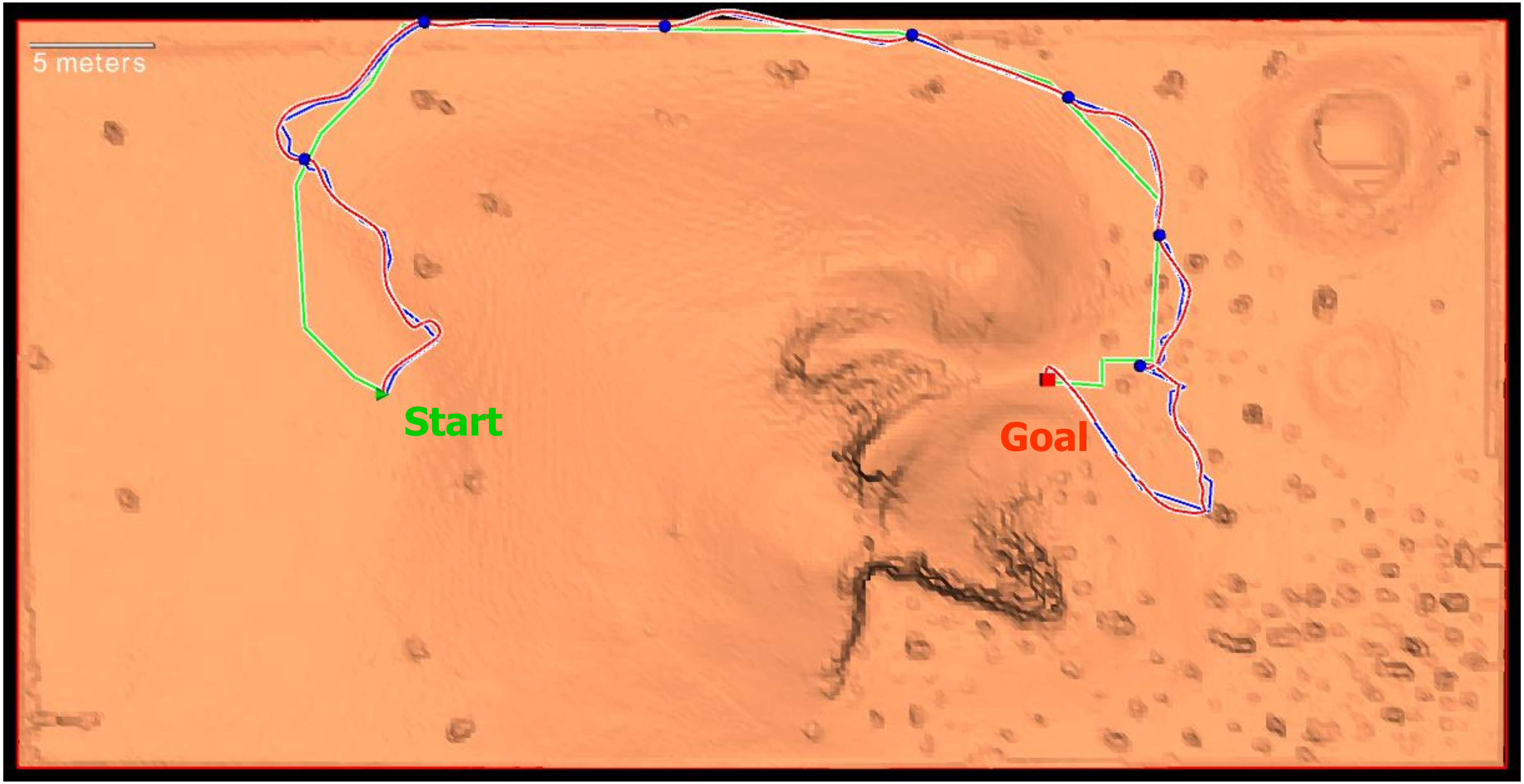


Fully Autonomous Navigation

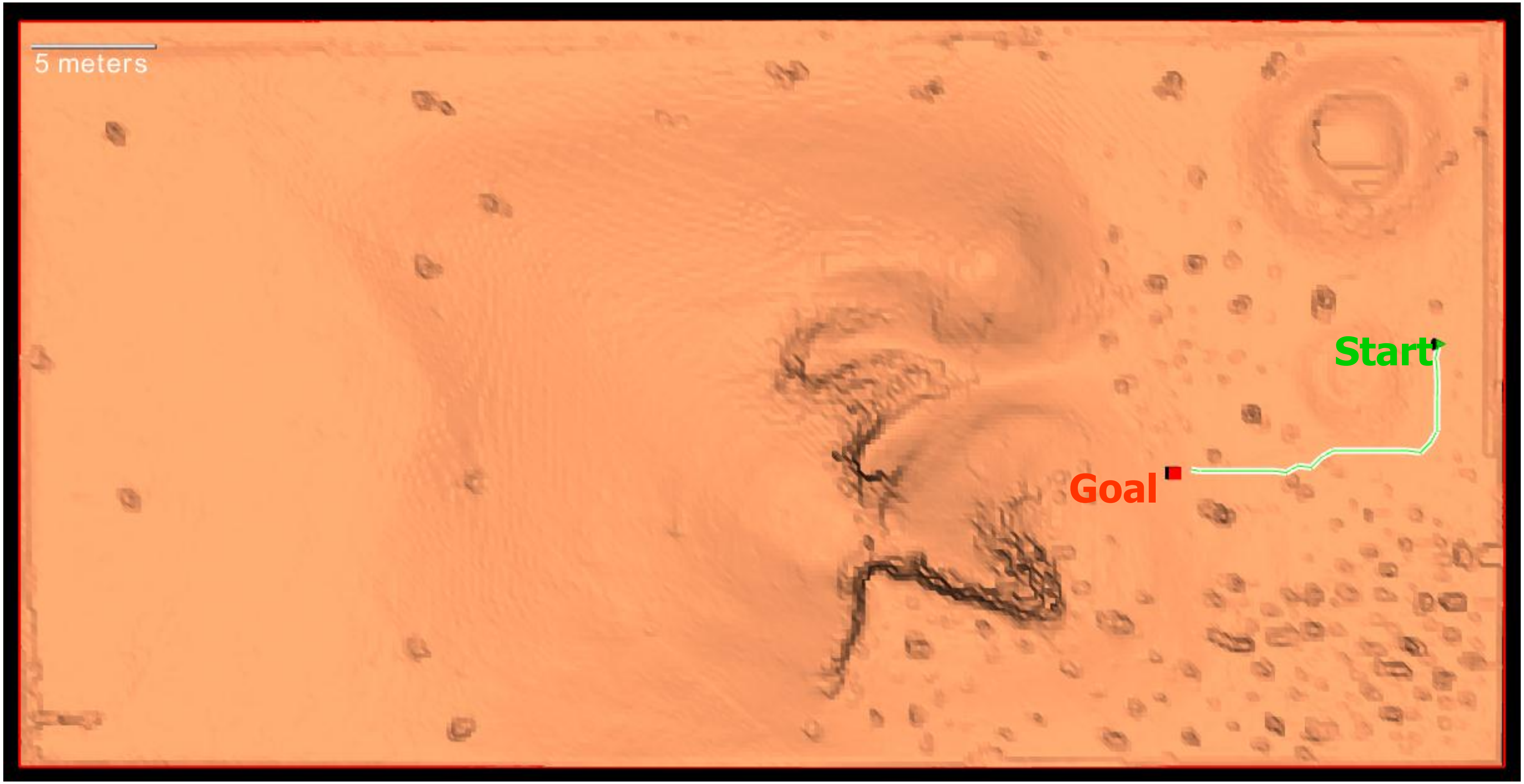
from flat to canyon



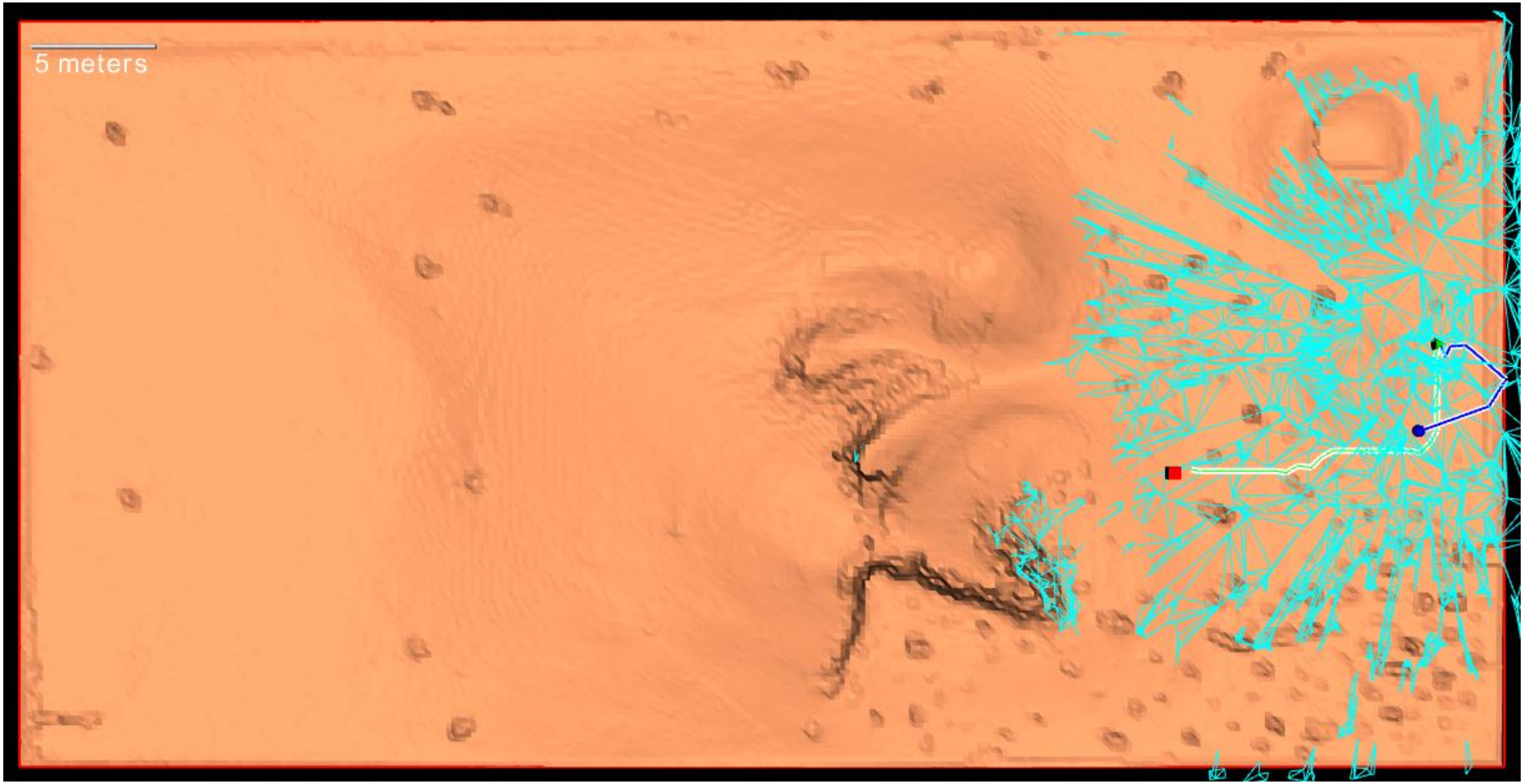
Fully Autonomous Navigation
from flat to canyon



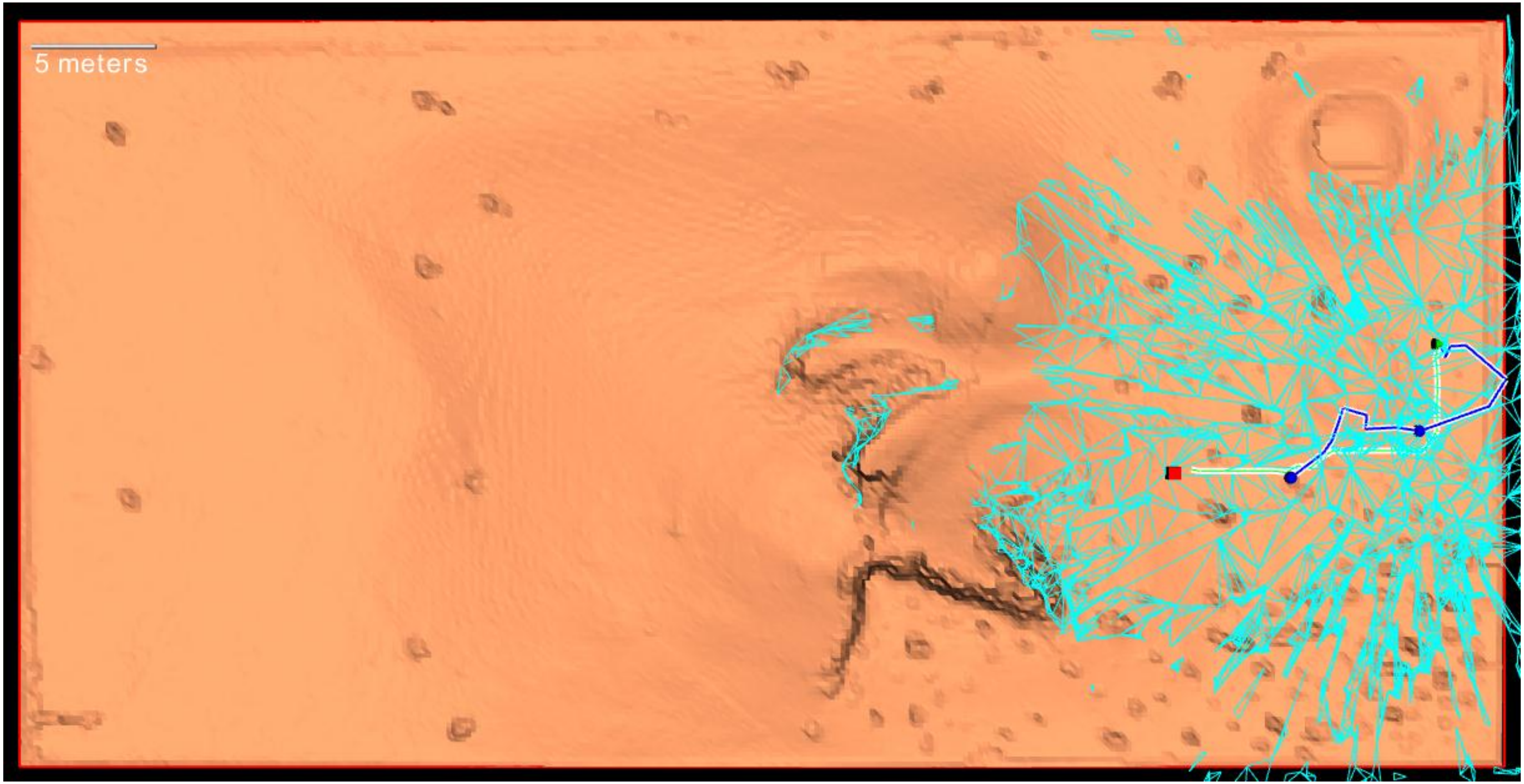
Fully Autonomous Navigation
from crater to canyon



Fully Autonomous Navigation
from crater to canyon

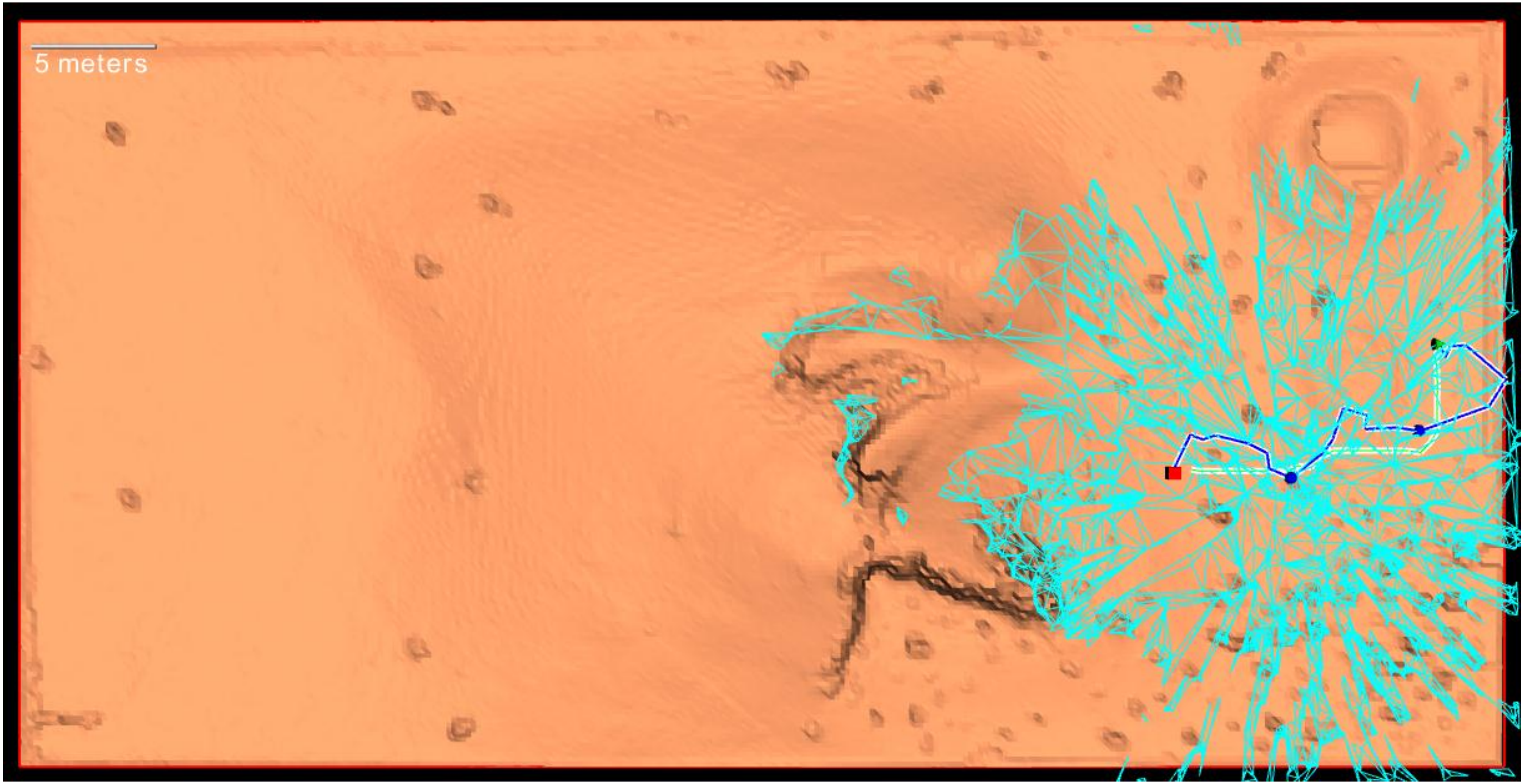


Fully Autonomous Navigation
from crater to canyon

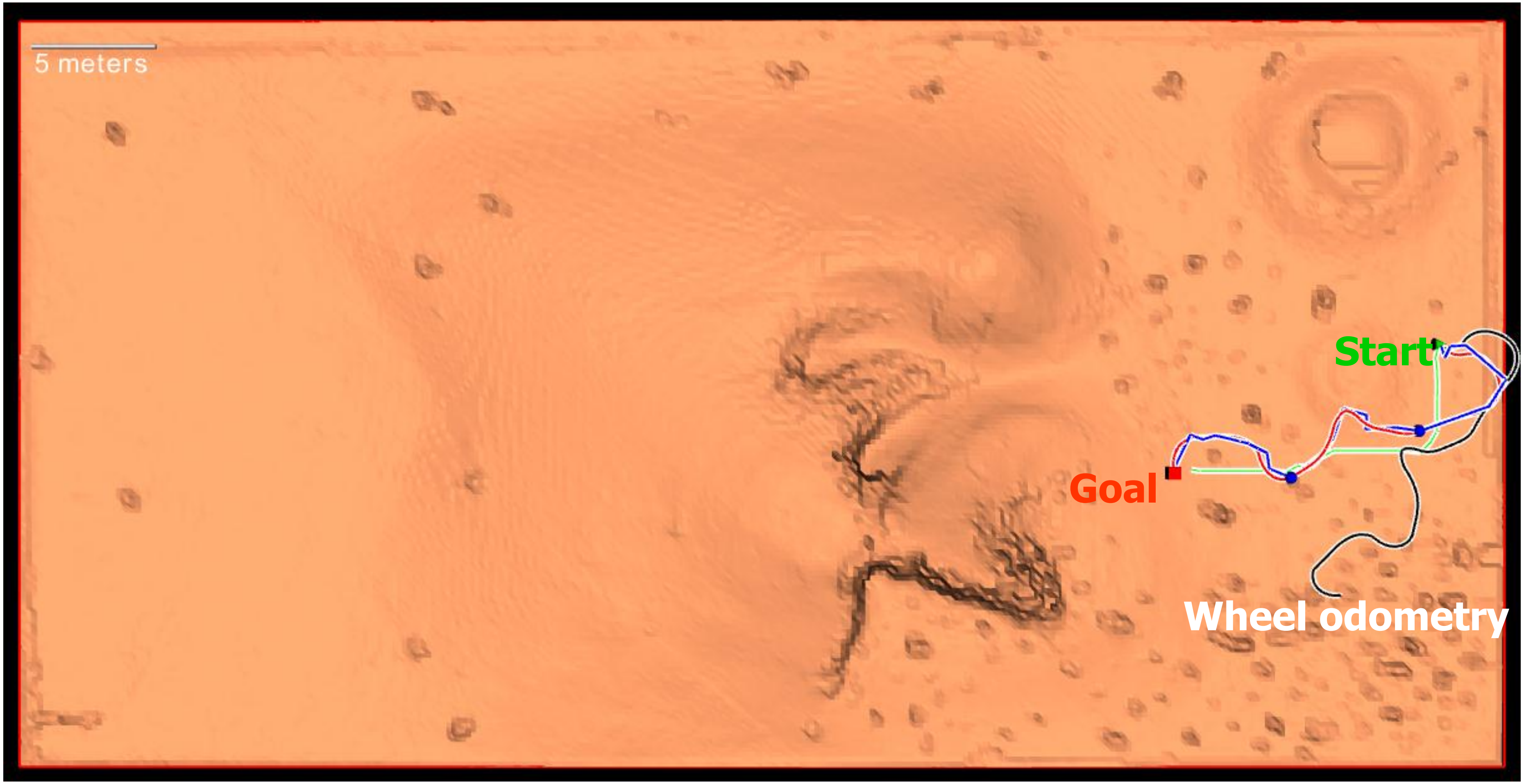


Fully Autonomous Navigation

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 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)