
UNIVERSITÀ
DEGLI STUDI
DI PADOVA

# Development and Implementation of Key Functionalities for a Lunar Rover Guidance Navigation and Control System

Simone Fortuna - 38th Cycle

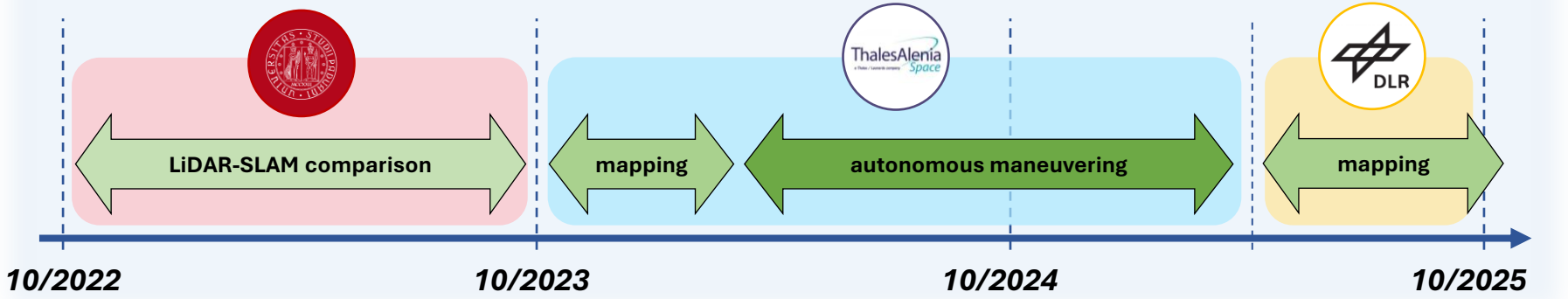
Supervisor: Prof. Marco Pertile
Co-supervisors: Andrea Merlo, Sebastiano Chiodini, Andrea Valmorbida

Admission to the thesis evaluation procedure - 15/10/2025

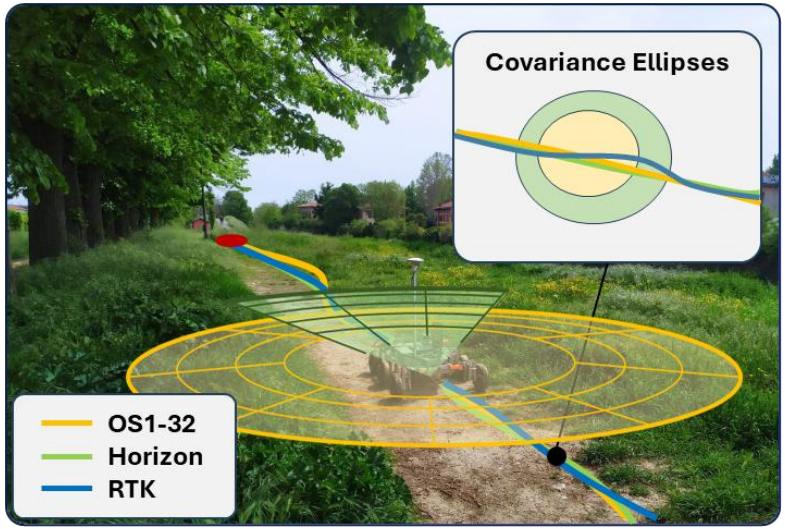
# Main activities of PhD

## Main Research Activities

A. LiDAR-SLAM systems comparison
B. Terrain Mapping in Unstructured Environments
C. Maneuvering Strategies for Lunar Rovers

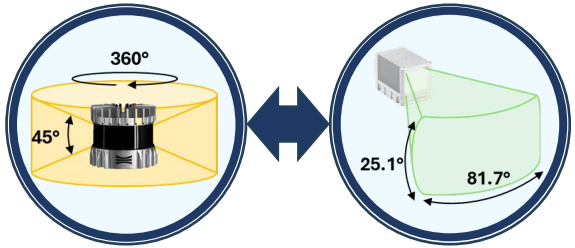


# #LiDARs - Overview



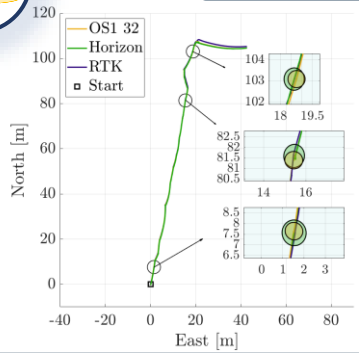

## Ouster OS1 vs Livox Horizon

- Motorized Optomechanical vs MEMS Scanner
- SLAM Algorithm used: FAST LIO 2
- Comparison of metrological aspects



# #LiDARs - Comparison

## Accuracy



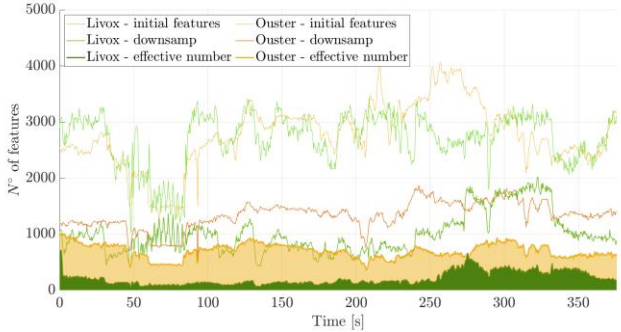

average ATE



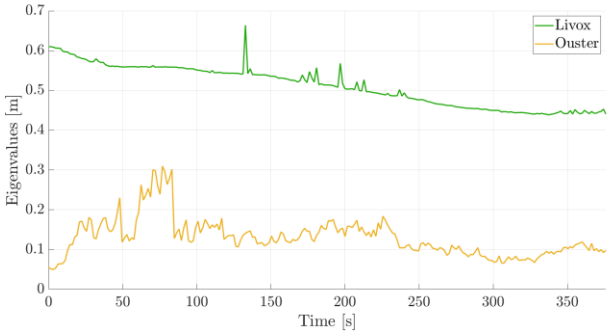


0.24 m ~ 0.25 m

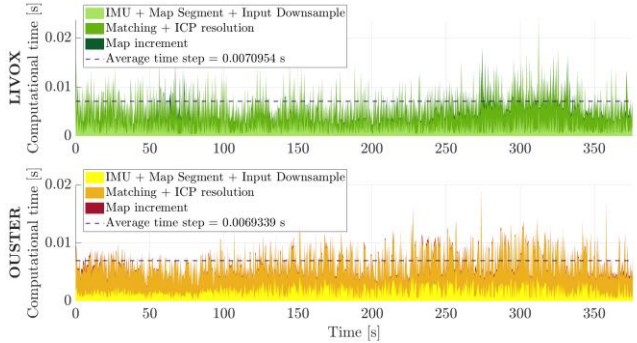
## Reliability



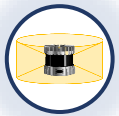

## Uncertainty




## Efficiency



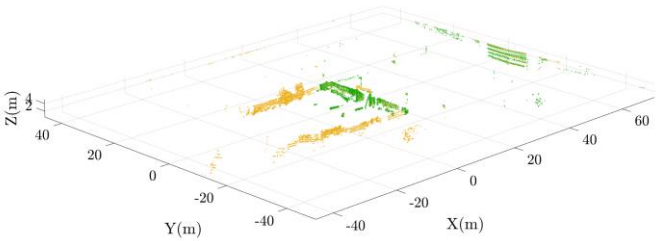
# #LiDARs - Results

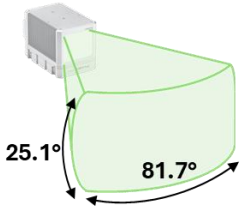


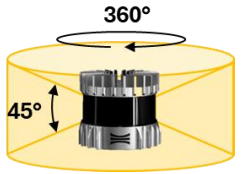
**Performances are comparable!**

*Crucial features:*

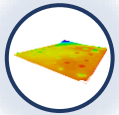
- *Deeper vs Wider FOV*
- *Features dispersion and density*



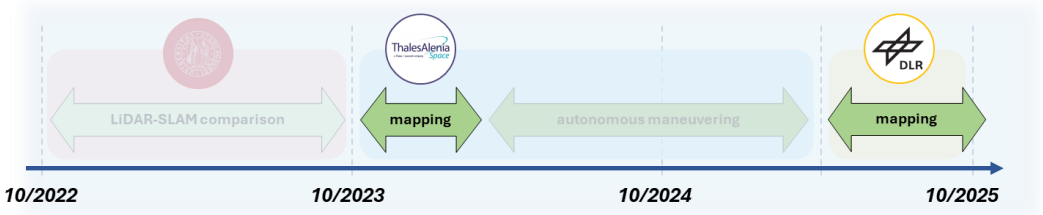

| | Livox Horizon | Ouster OS 1 |
|---|---|---|
| ***ATE error*** | ++ | ++ |
| ***Uncertainty*** | + | +++ |
| ***Reliability*** | ++ | ++ |
| ***Efficiency*** | + | +++ |
| ***Cost*** | $ | $$$ |

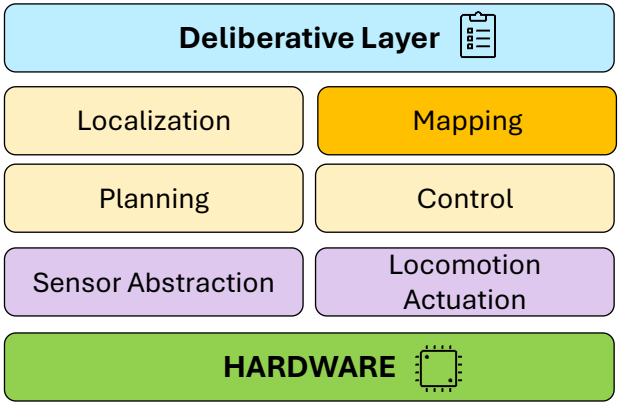


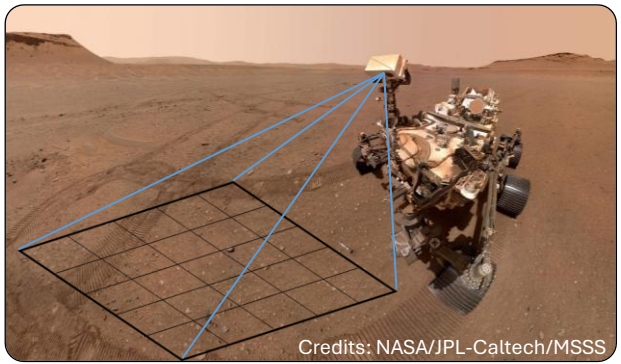
## Terrain Mapping in Autonomous Navigation

Traversability maps: what information could be registered?

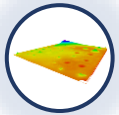
- **Geometric** (e.g., elevation, slope, roughness)
- **Semantic** (e.g., sand, bedrock, rock)

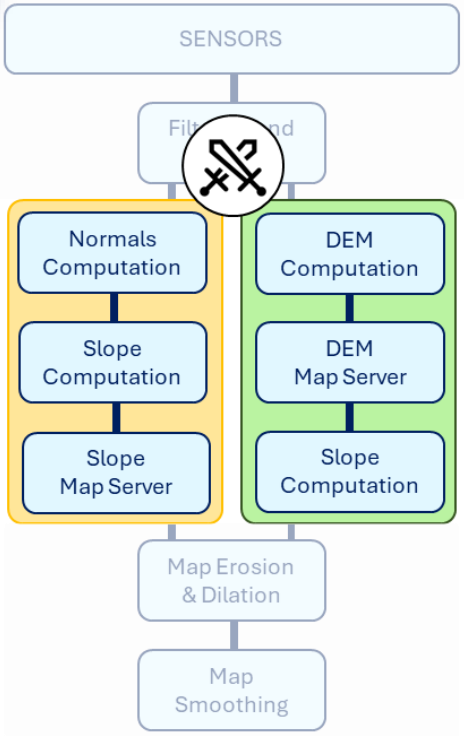


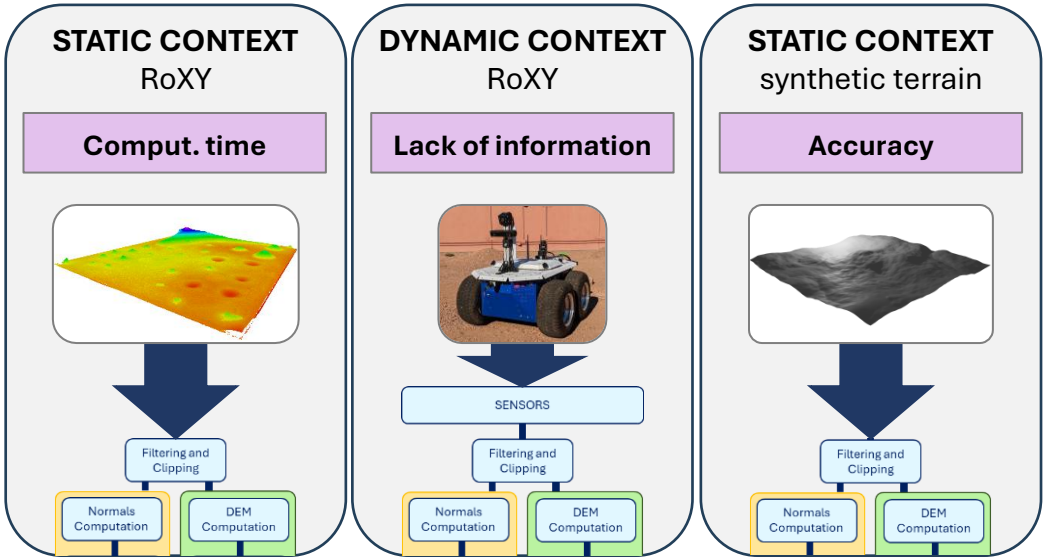



# #GeoMap - Pipeline Comparison

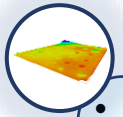




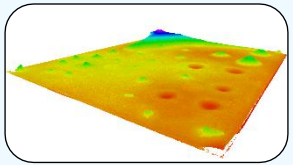

**Objective**: speed up real-time slope map construction by avoiding normals and using DEMs

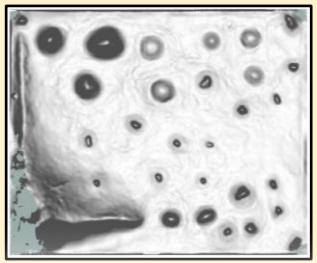


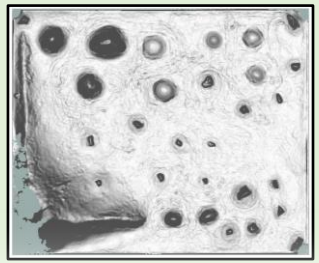
# #GeoMap - Results



- **STATIC CONTEXT**, RoXY





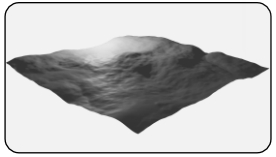

DEM pipeline is more than 4 times faster

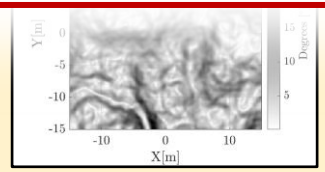
- **DYNAMIC CONTEXT**, RoXY

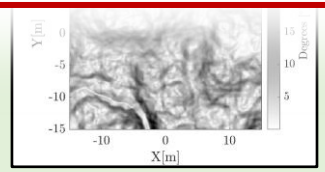
| Normals Computation pipeline | | Digital Elevation Model pipeline | |
|---|---|---|---|
| Normals computation (*) | $17468ms$ ($17373ms$) | DEM building (**) | $4335ms$ ($4245ms$) |
| Slope calculation | $209ms$ | Slope calculation | $15ms$ |

(*,**) Times to compute rough normals or DEM, respectively.

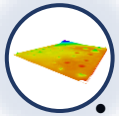
- **STATIC CONTEXT**, synthe



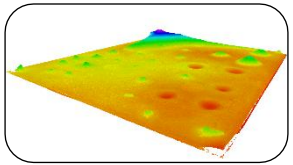


# #GeoMap - Results

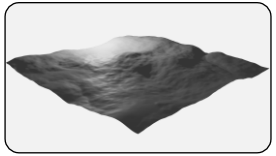


- **STATIC CONTEXT**, RoXY

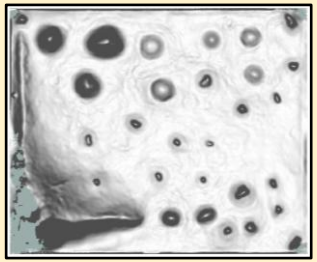


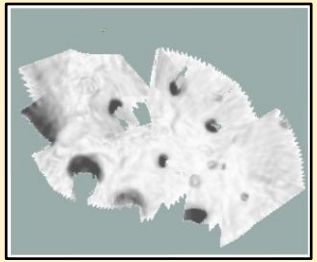
- **DYNAMIC CONTEXT**, RoXY

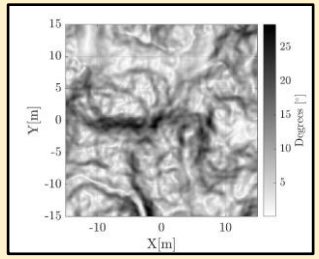
- **STATIC CONTEXT**, synthetic



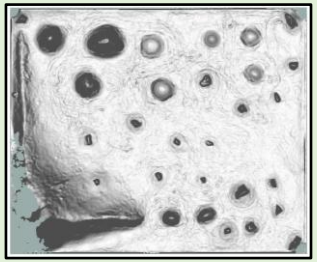
**Normals**

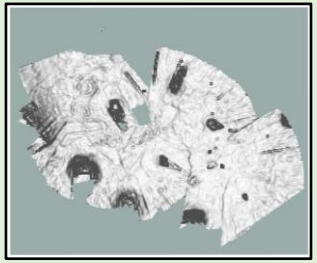


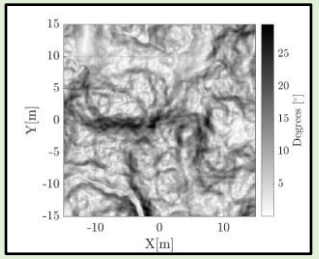





**DEM**



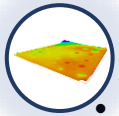




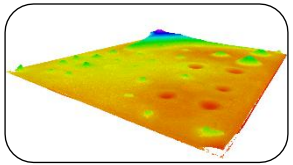

DEM pipeline is more than 4 times faster

DEM shows more defects due to lack of information

# #GeoMap - Results

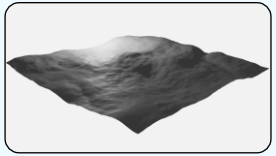


- **STATIC CONTEXT**, RoXY

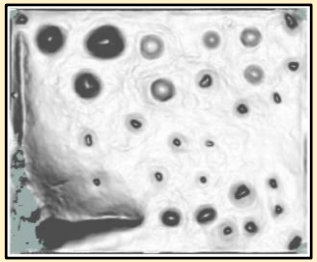


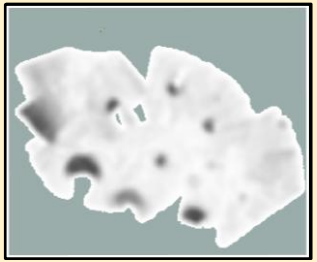
- **DYNAMIC CONTEXT**, RoXY

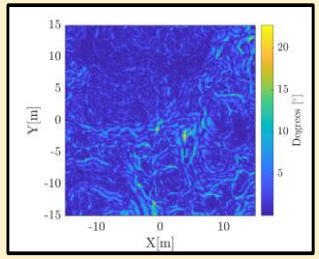
- **STATIC CONTEXT**, synthetic



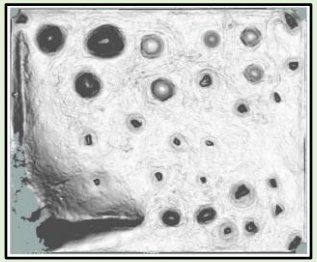
**Normals**

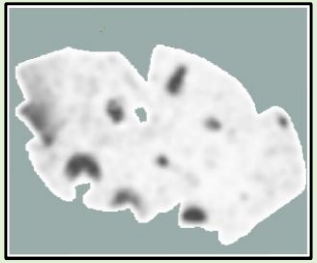


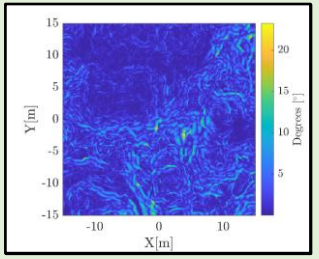





**DEM**





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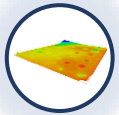
DEM shows more defects due to lack of information

**RMSE**

3.101° < 3.275°

# #SemMap - LRU & Task Overview



**Lightweight Rover Unit**

*"A mobile robot for exploration of unknown, impassable and hard to access terrain"*

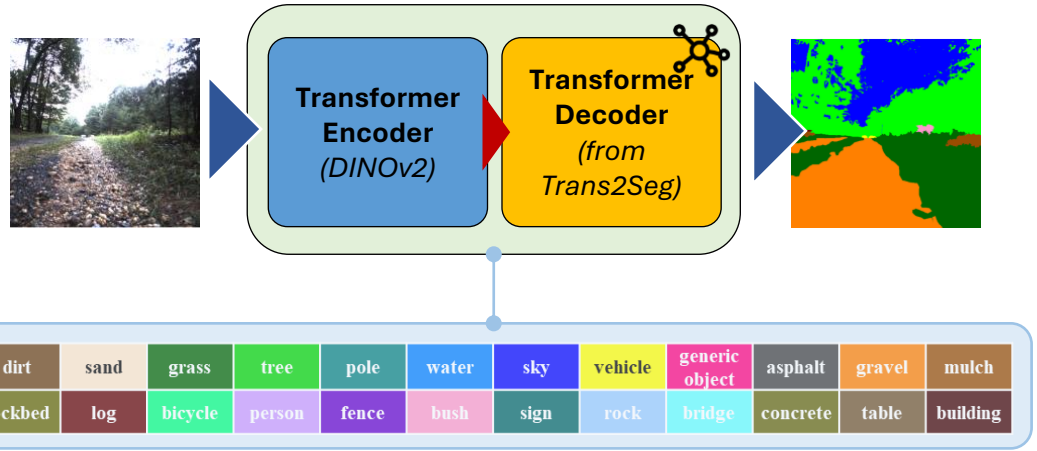
**Objective:**
**Insert Semantics in Local Mapping**

- Integration of Neural Network
- Solve time consistency of labels
- Combine geom&semantic costs

# #SemMap - Network Integration

## Semantic Segmentation Network

- Trained on RUGD dataset
- Needs RGB 504x504 images
- Integrated within a ROS 2 client-server architecture




! ***NON-SPACE DOMAIN!***

# #SemMap - Network Integration

## Semantic Segmentation Network

- Trained on RUGD dataset
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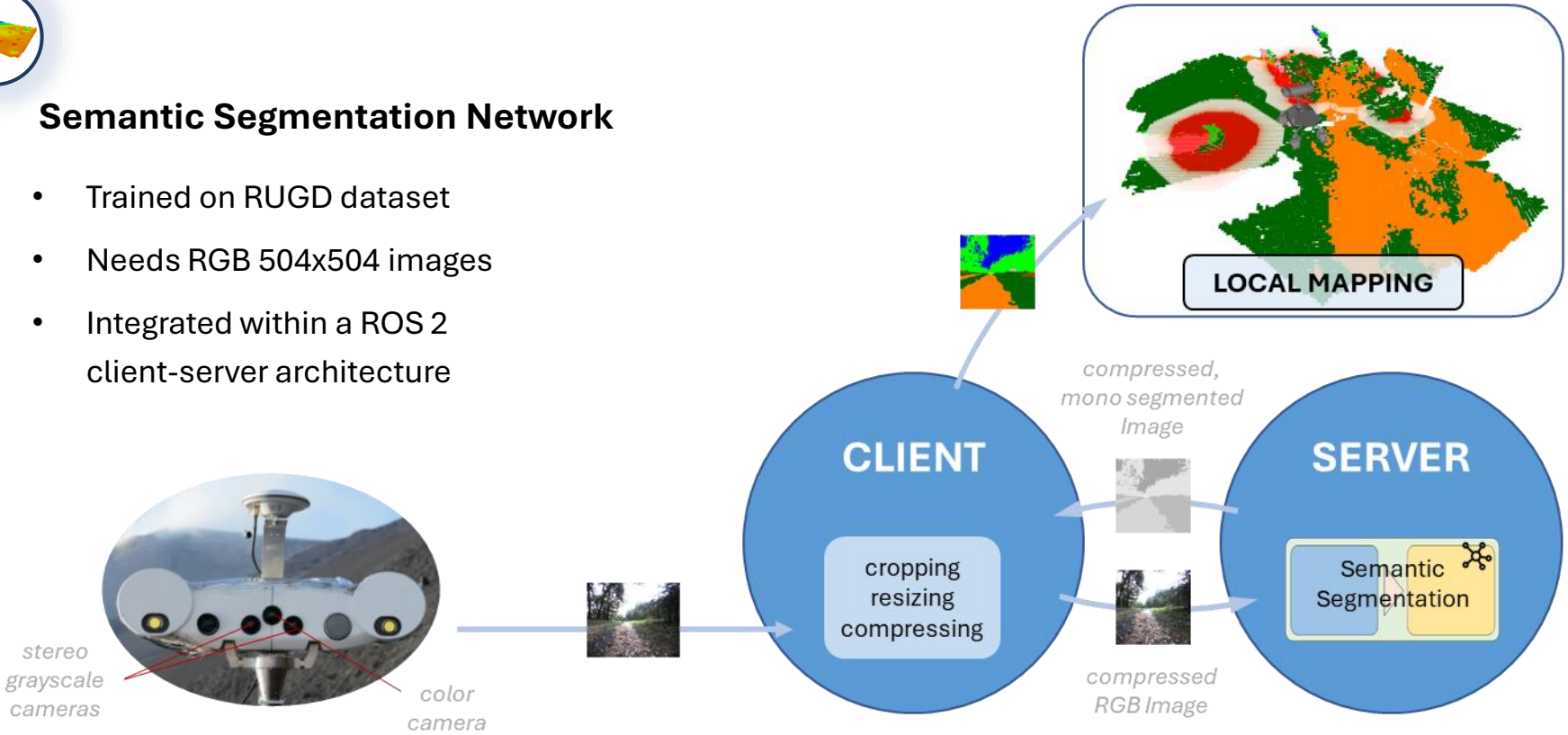
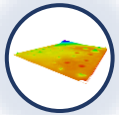


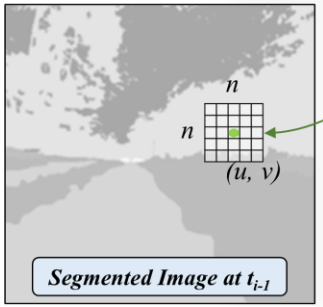
# #SemMap - Network Integration

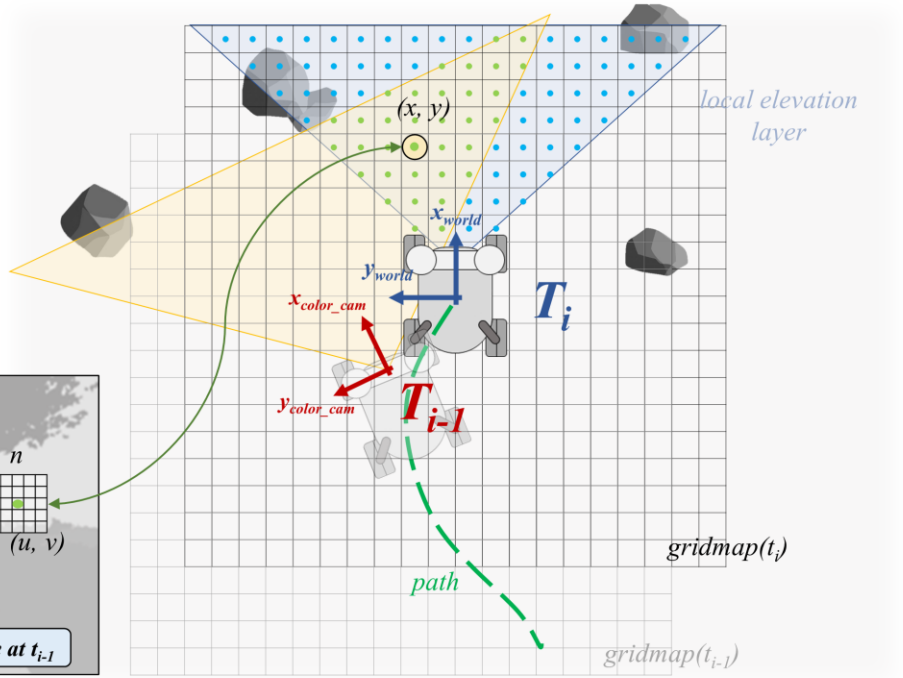


**Problem: color camera has no-depth info !**

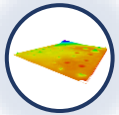
1. Projection of map points into last segmented image
2. Consideration of **n x n** pixels at **(u,v)**
3. Computation of label and entropy **(l, e)**

$$\begin{cases} \boldsymbol{l} = \text{most present label} \\ \boldsymbol{e} = -\dfrac{1}{\log_2(24)} \displaystyle\sum_{k=1}^{24} p_k \log_2(p_k) \\ \text{with } p_k = -\dfrac{h_k}{n^2} \end{cases}$$



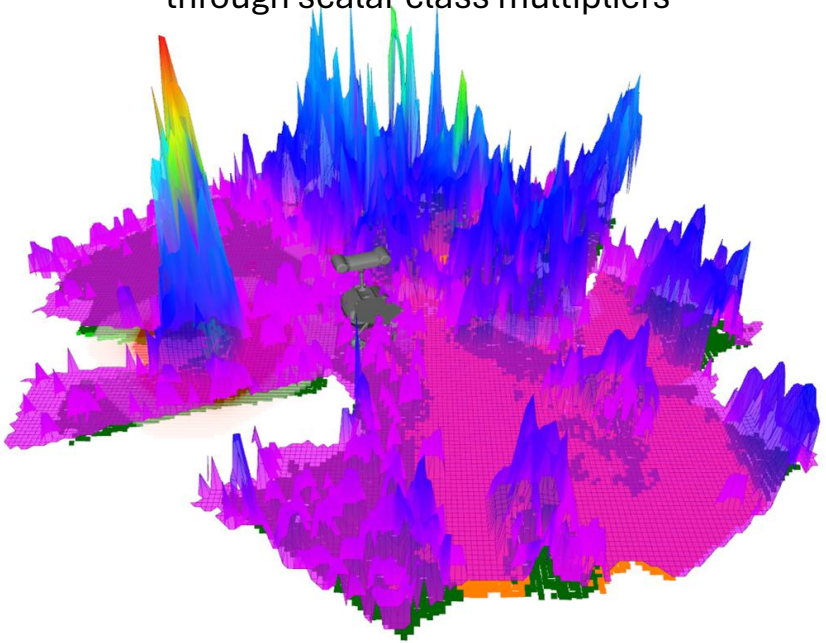



# #SemMap - Adopted Solutions



- **Time Consistency**: Update the label looking at entropies as uncertainty indicator

- **Merge of Costs**: Update geometric costs through scalar class multipliers



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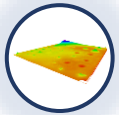

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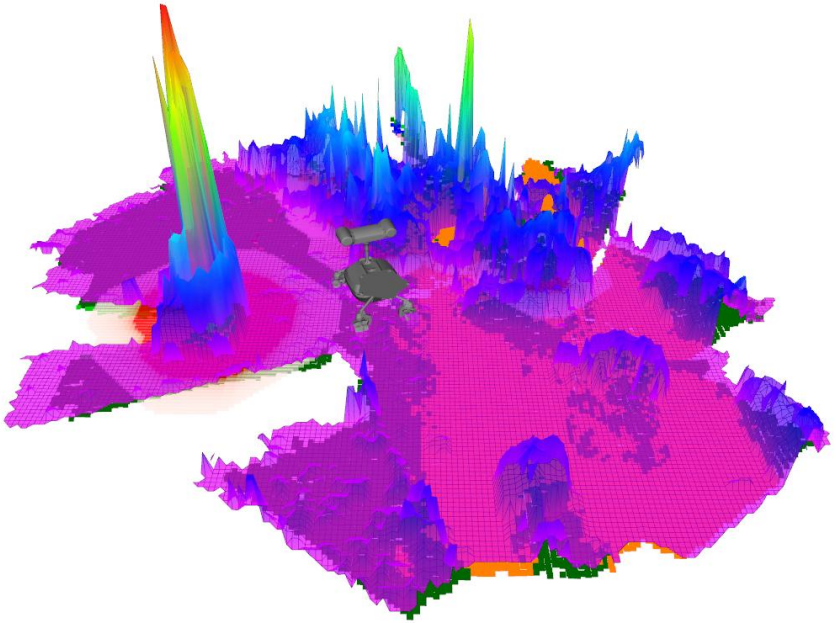
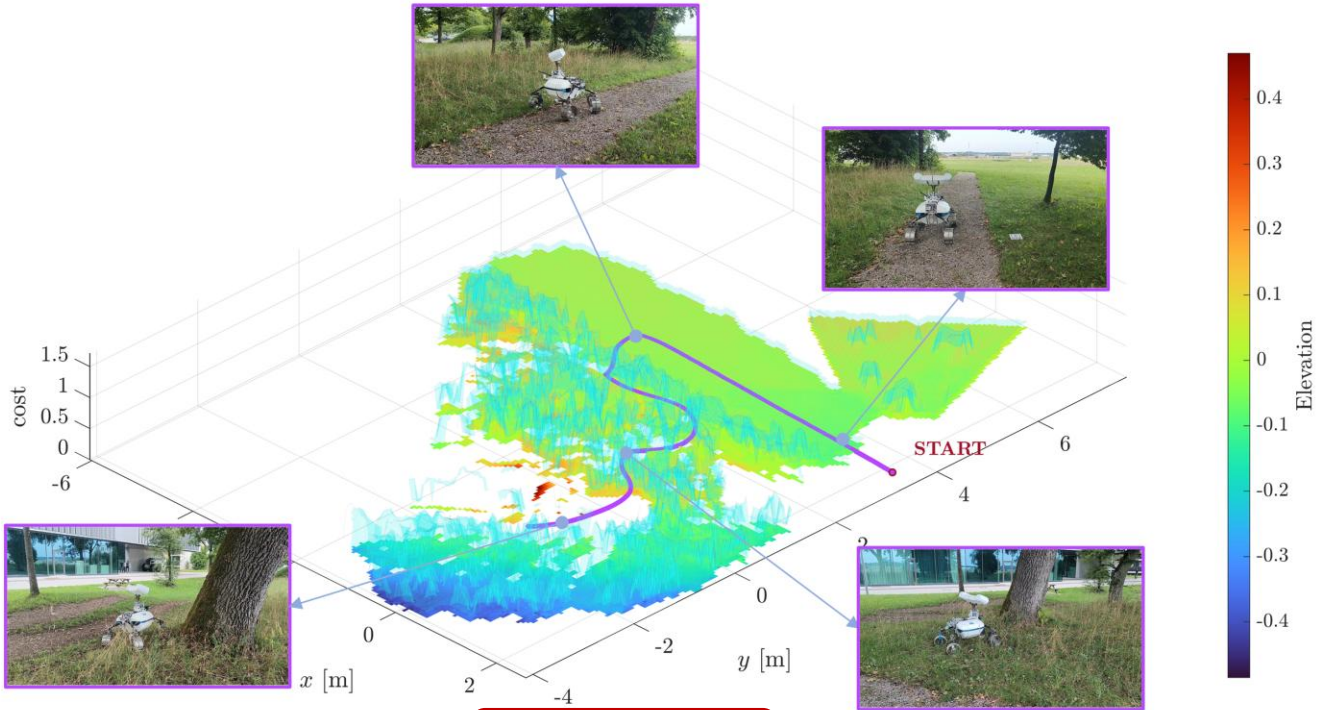


## Geometric VS Semantic&Geometric

**1.** Bush Crossing

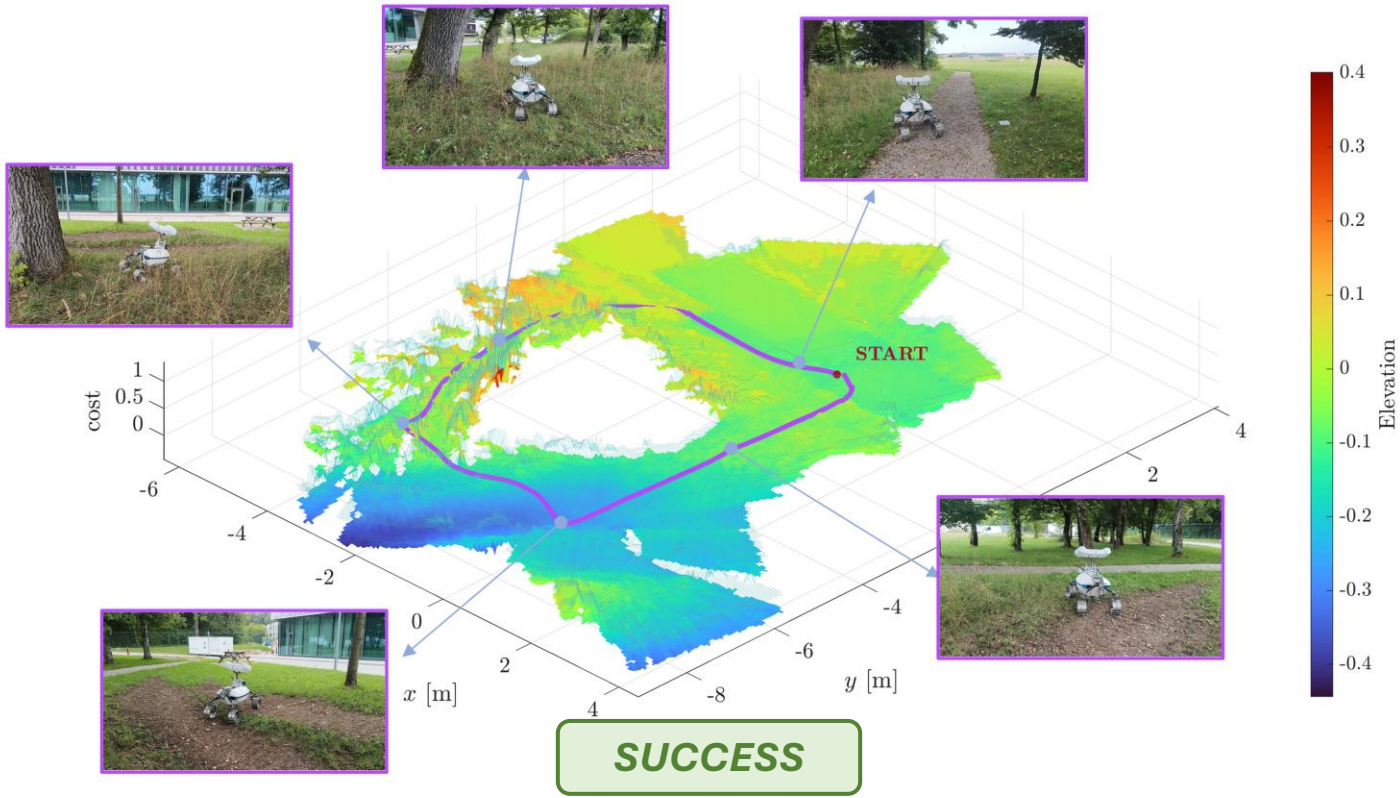
**2.** Water Crossing

# #SemMap - Bush crossing, geometric




**FAIL**

# #SemMap - Bush crossing, semantic




**SUCCESS**

# #Man - Aut. Maneuvering Problem

## Autonomous maneuver selection for non-holonomic robotic vehicles

- Non-holonomic
- No skid steering
- Featuring a set of maneuvers
- Different kinematic limits for each maneuver

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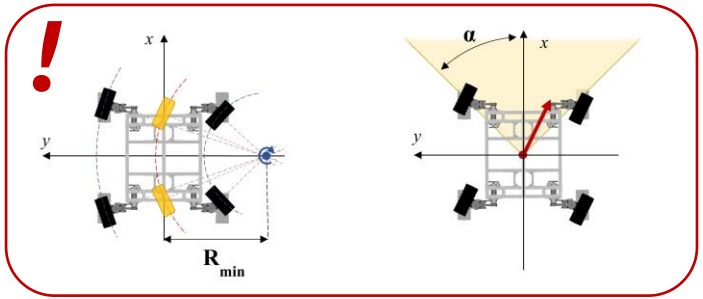
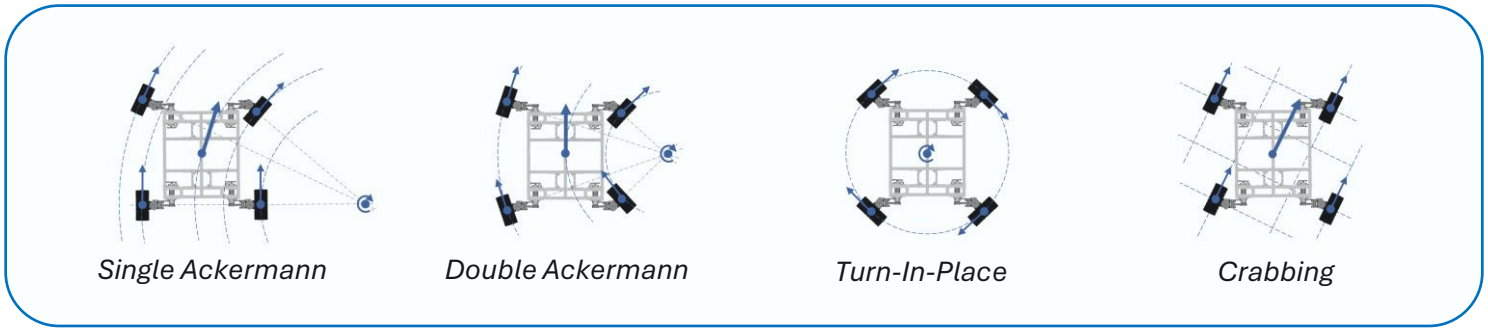
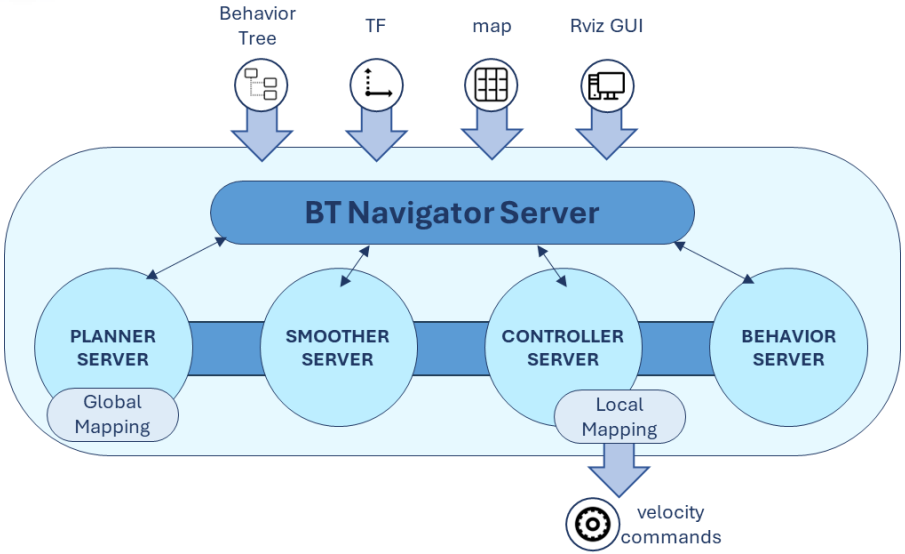
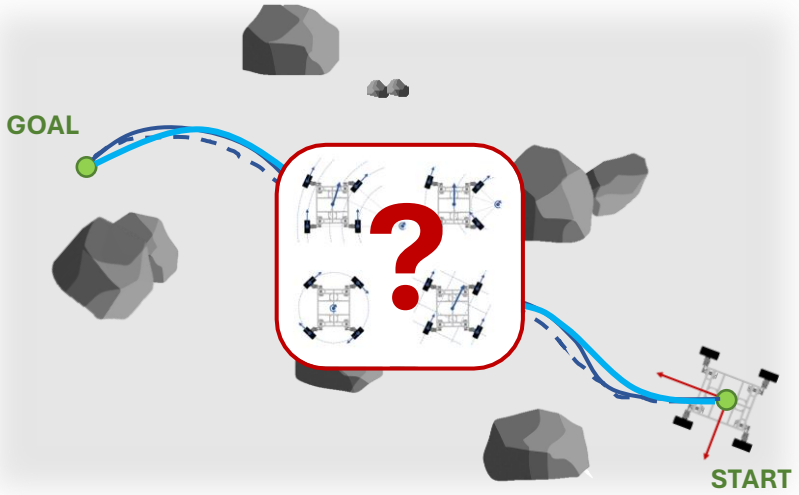


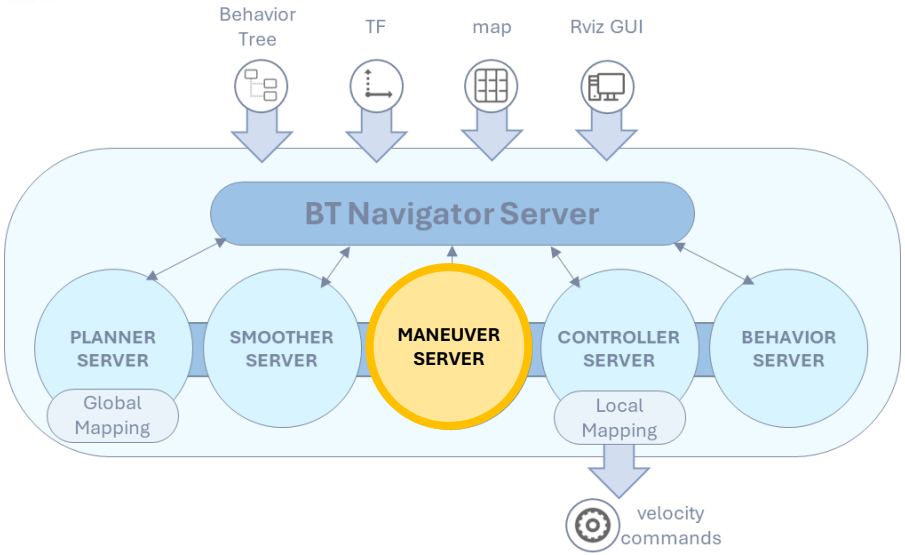
# #Man - Nav2 framework limits



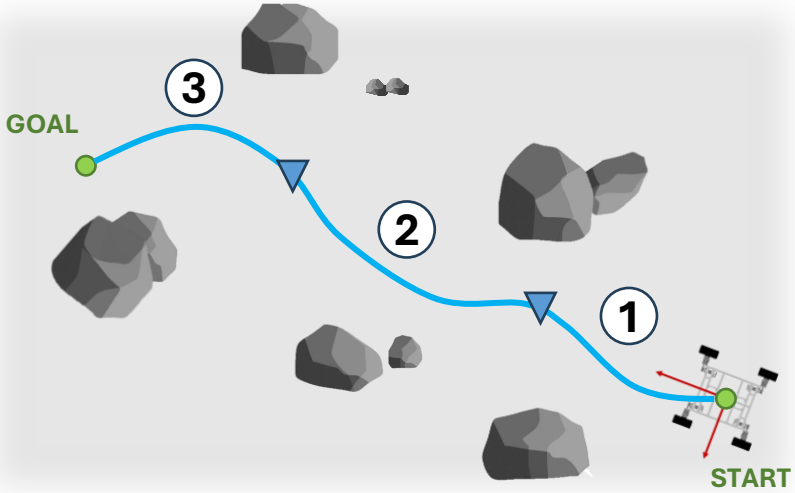

- Is the planned trajectory feasible?
- What locomotion mode must be chosen?
- What kind of controller must be used?



# #Man - Maneuver Server



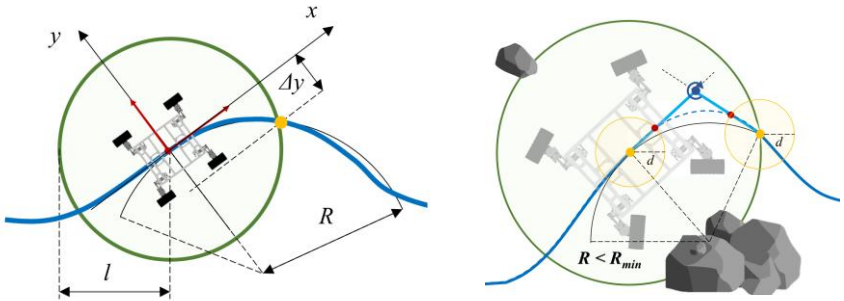

- ✓ Modularity
- ✓ Isolation of functionality
- ✓ Ease of interpretation



# #Man - Path Splitting Logics

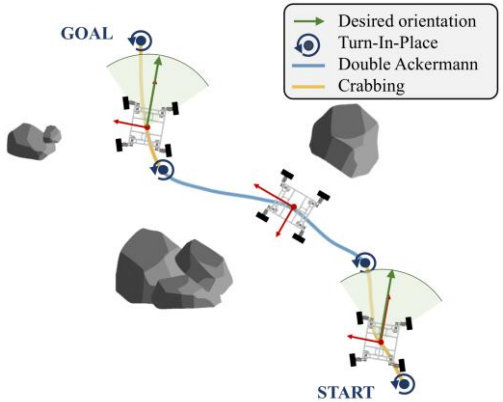
## Nav mode: ***Ackermann + Point-turn***

- *Analyze curvatures (Pure-Pursuit concept)*
- *Split if* $\boldsymbol{R = \frac{l^2}{2\Delta y} < R_{min}}$
- *Set PT spot through a geometric construction*



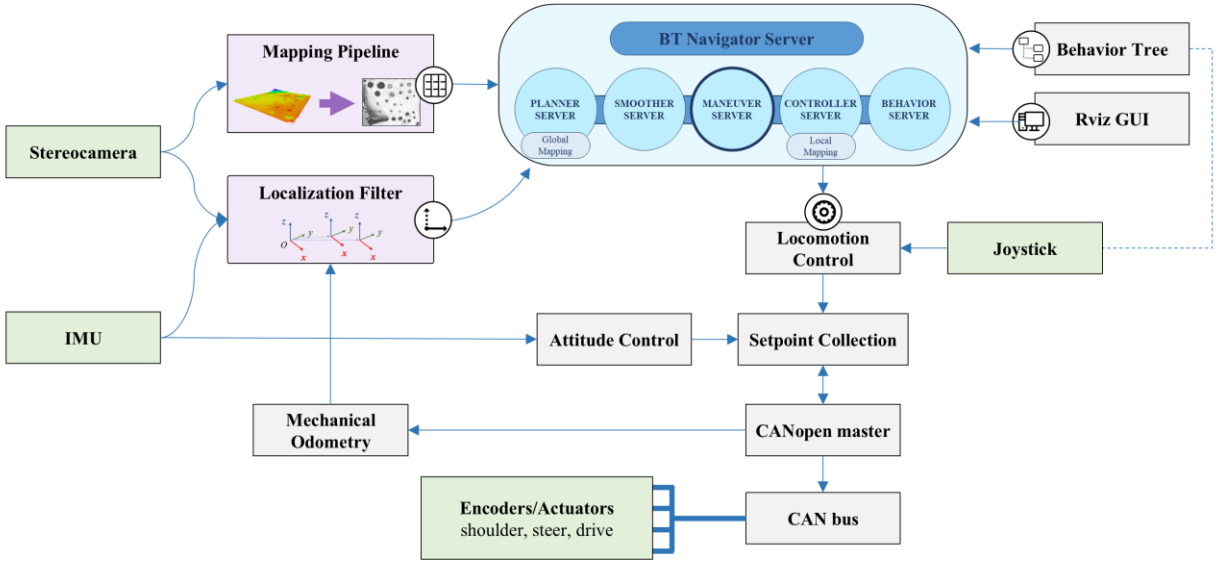

## Nav mode: ***Heading-Preserving***

- *Receive a preferred direction*
- *Translate while keeping a specific orientation*
- *Ackermann + Point-turn when not feasible*



## Integration within the EMRS framework

- DEM Mapping Pipeline
- AutoNav (Nav2-based)
- Behavior Tree



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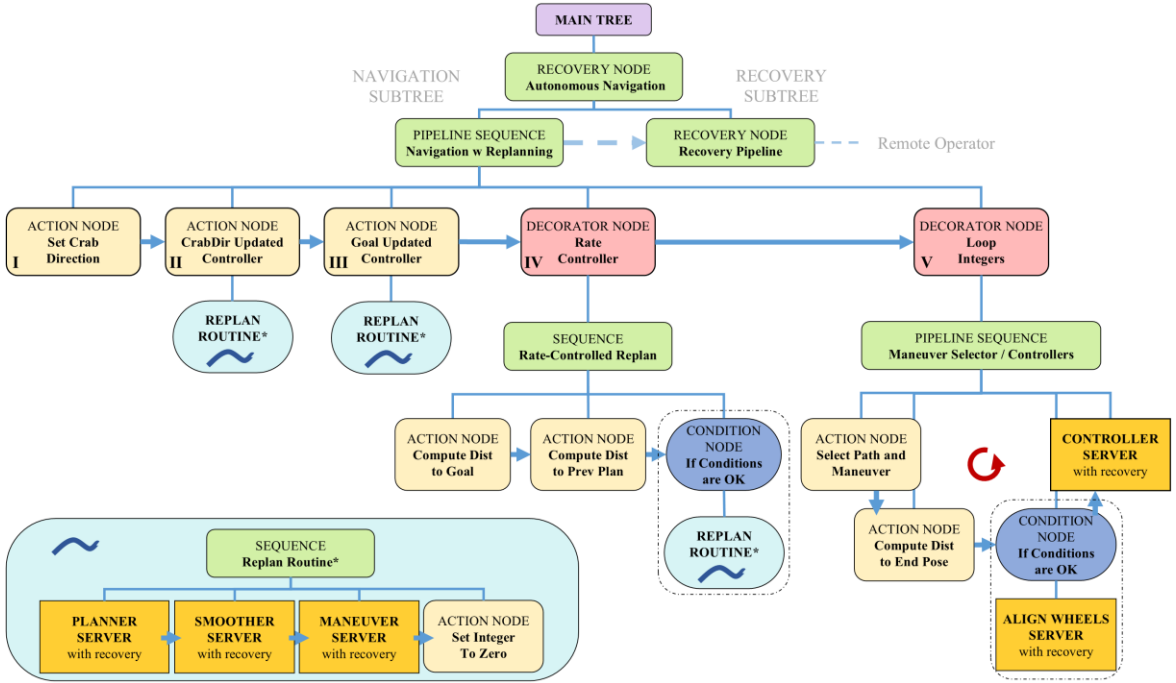
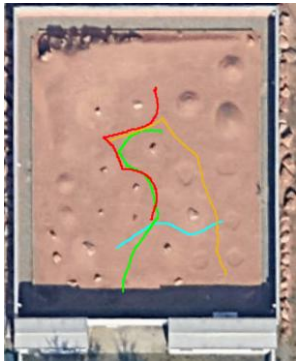
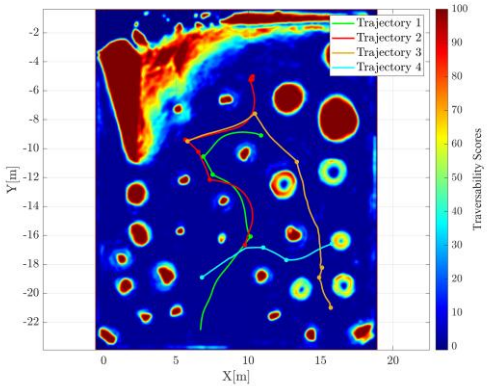


# #Man - Tests at TAS-I RoXY facility

## Tests with the EMRS rover

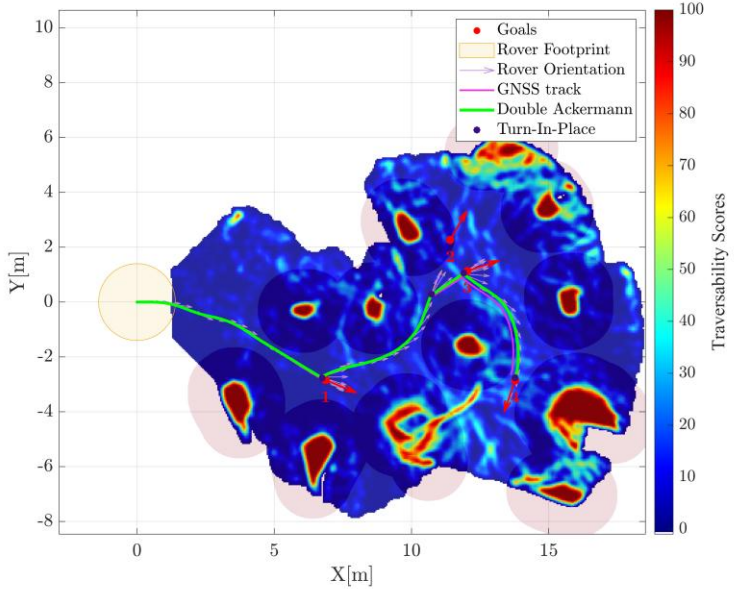
- Starting from a random pose in RoXY
- Random goals and preferred orientations
- Showing two routes for each nav mode

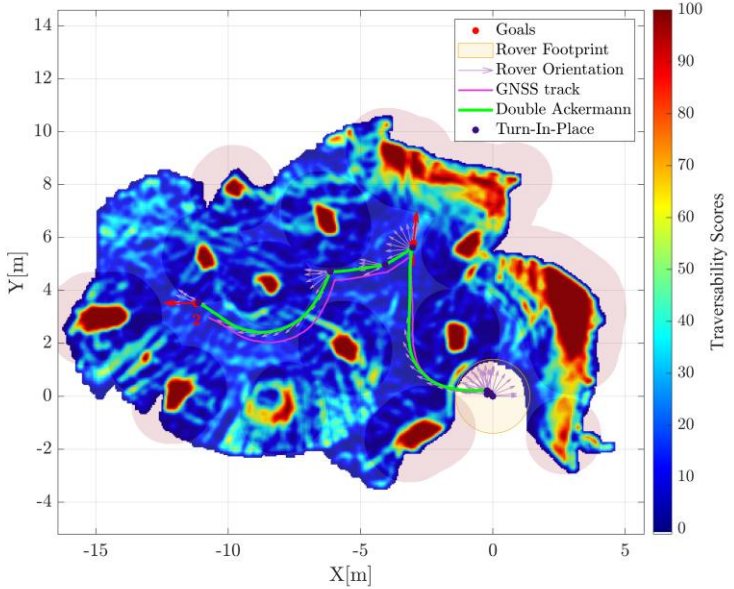





# #Man - Tests at TAS-I RoXY facility

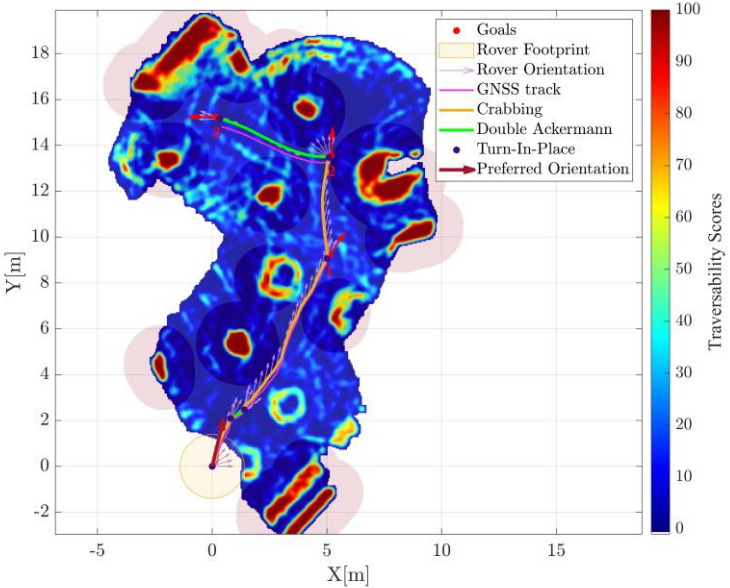
Nav mode: ***Ackermann + Point-turn***

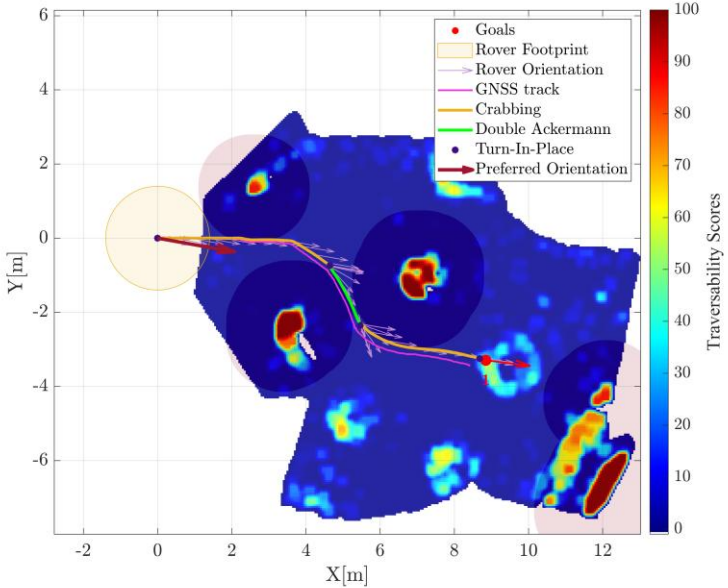


# #Man - Tests at TAS-I RoXY facility

Nav mode: ***Heading-Preserving***



# Timing

| WBS NUMBER | TASK TITLE | % OF TASK COMPLETE | T1 | | | T2 | | | T3 | | | T4 | | | T1 | | | T2 | | | T3 | | | T4 | | | T1 | | | T2 | | | T3 | | | T4 | | | +1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | O | N | D | J | F | M | A | M | J | J | A | S | O | N | D | J | F | M | A | M | J | J | A | S | O | N | D | J | F | M | A | M | J | J | A | S | O |
| **1** | **Skills Acquisition and Literature Review** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1.1 | Study of Visual SLAM | 100% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1.2 | Acquiring skills in programming and ROS/ROS 2 framework | 100% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1.3 | Navigation sensors and strategies review | 100% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1.4 | Rover GNC systems/architectures review | 100% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **2** | **Investigation and Planning of key functional elements for the rover GNC system** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2.1 | Use cases and requirements definition for the lunar rover | 100% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2.2 | Investigation and design of terrain mapping techniques | 100% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2.3 | Definition of autonomous maneuvering and navigation strategy | 100% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **3** | **Development and Integration of core Autonomous Navigation functionalities** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3.1 | Development of mapping algorithms for outdoor environments | 100% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3.2 | Development of autonomous manuevering algorithms for the lunar rover | 100% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3.3 | Integration of proposed strategies into the rover's software architecture | 100% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **4** | **SW/HW tests and navigation strategies validation** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 4.1 | Test campaign | 100% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 4.2 | Test results analysis | 90% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **5** | **Thesis writing and reports/articles redaction** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 5.1 | Writing reports | 100% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 5.2 | Article redaction | 100% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 5.3 | PhD Thesis | 75% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

# Thanks for the attention!


UNIVERSITÀ DEGLI STUDI DI PADOVA