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LEVERAGING A MISSION DIGITAL TWIN TECHNOLOGY FOR AUTONOMOUS LUNAR ROVER NAVIGATION AND SCENARIO VALIDATION

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Summary

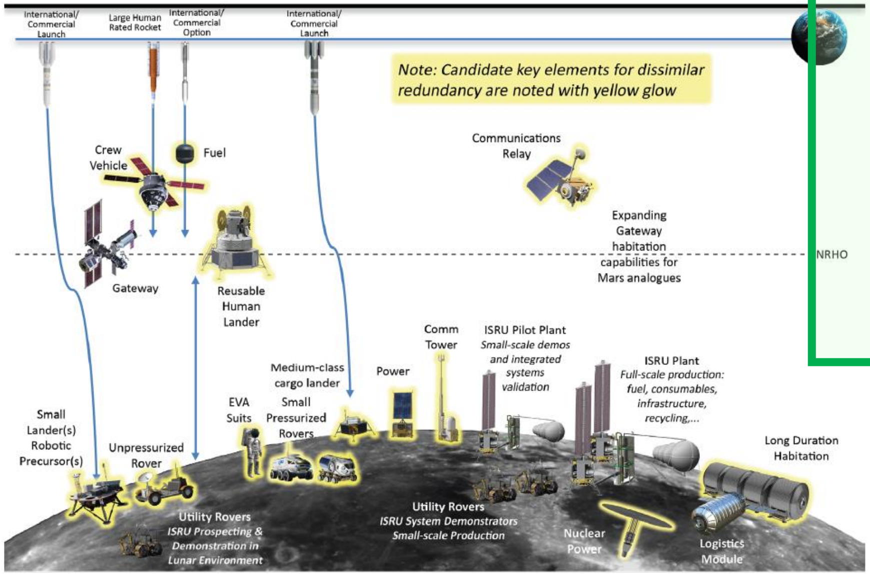
TELESPAZIO a LEONARDO and THALES company

SAPIENZA UNIVERSITÀ DI ROMA

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

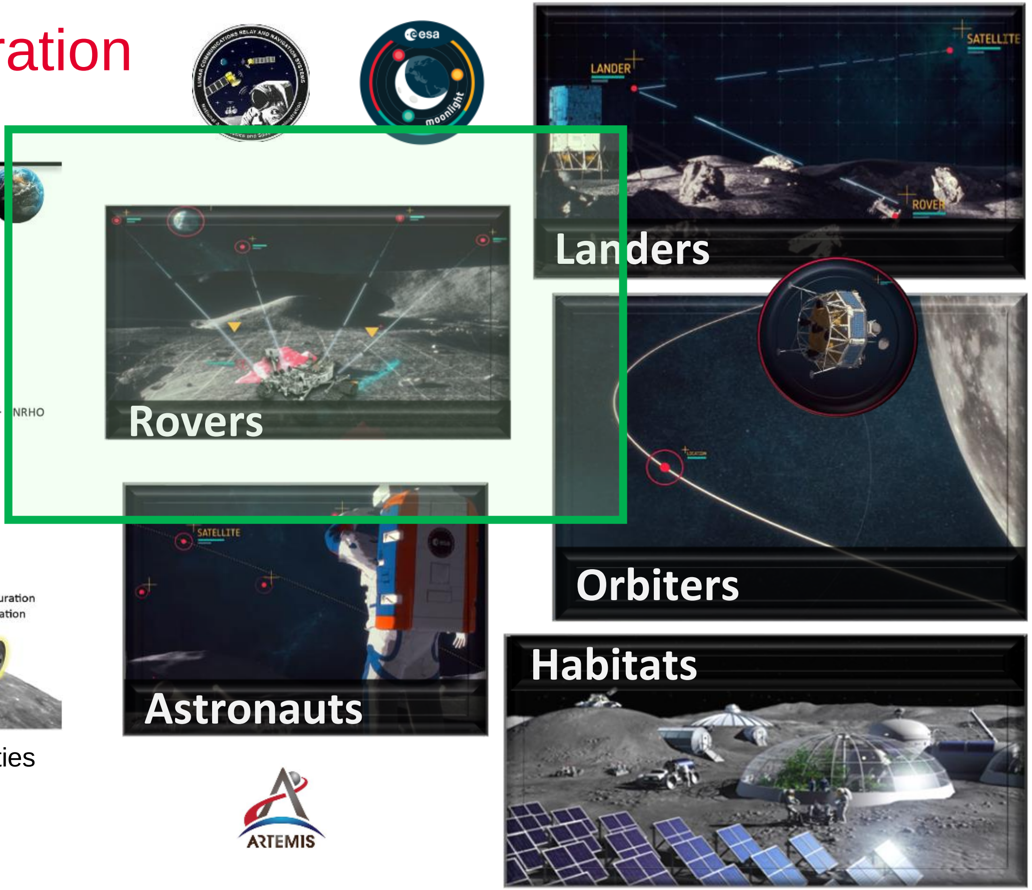
POLITECNICO MILANO 1863

The New Era of Lunar Exploration

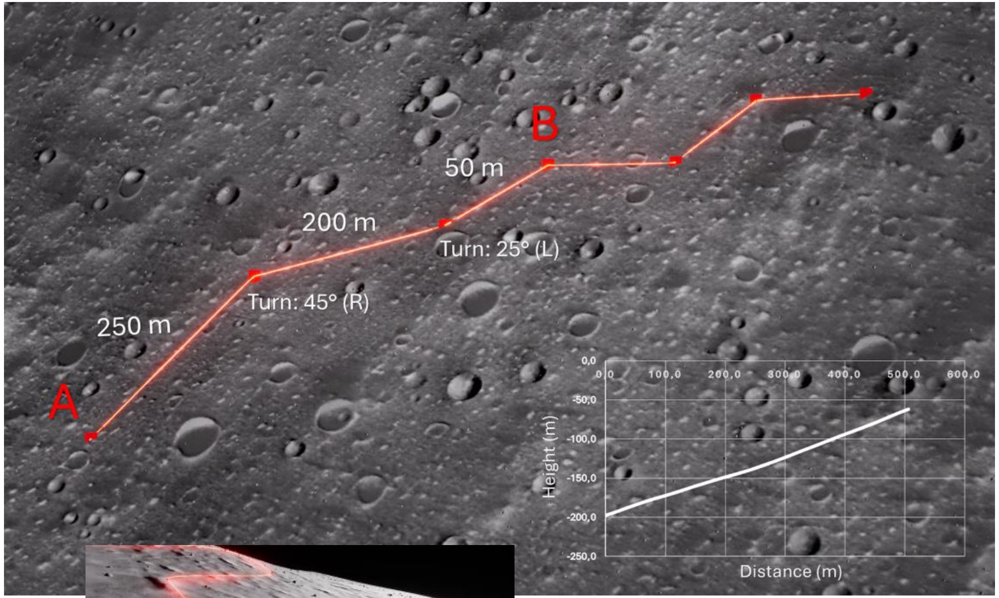


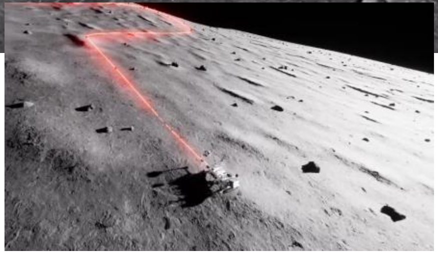
Infrastructure and mobile platforms for sustainable lunar activities

Credit: ISECG GER Supplement



Mission Scenario: Rover Trajectory over the Lunar South Pole

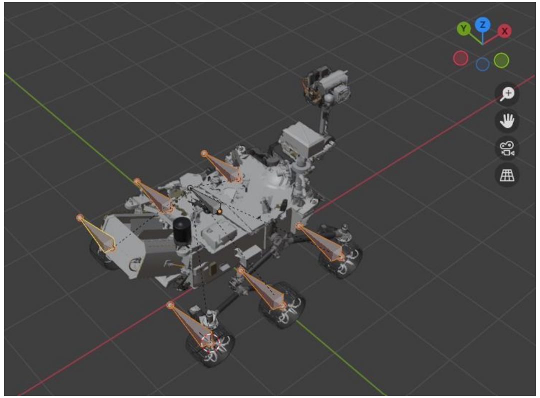


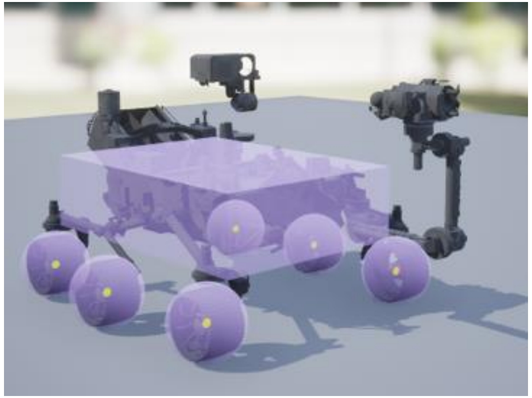


- Site: Shackleton Crater
- Reference rover trajectory was generated using an A* path planning algorithm – 500m trajectory
- Avoiding of terrain regions with slopes exceeding 20°
- Total Elevation Gain: 135m
- Average velocity of 1.5 m/s

➢ Synthetic Tile Resolution Augmentation, with Statistical Distribution of Small Craters, rocks and addition of Synthetic details via injected fractal noise to reproduce large-scale surface details.

Mission Scenario: Rover and Sensor Modeling





Ref. Perseverance Rover

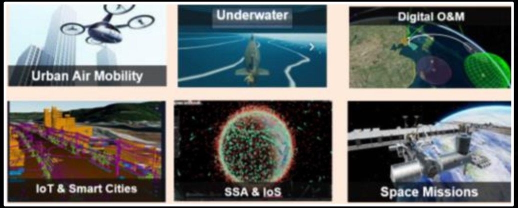
Parameters	Value
Torque Curve	Assumed Linear
Maximum Torque [Nm]	4500
Maximum RPM	4500
Maximum Steering [deg]	50
Mass [Kg]	300

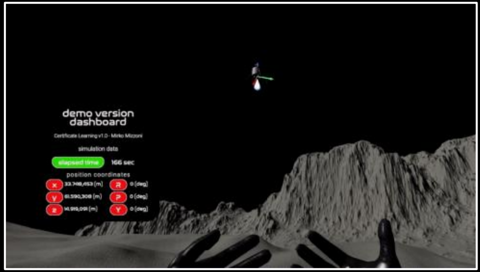
Camera Parameter Pinhole camera model	Value
Camera FOV	96° × 73°
Focal length	19.1 mm
Stereo baseline	42.4 cm
Sensor size	32.77 × 24.58 mm
Image resolution	1378 × 720 px
Left camera position	[1.0, 0.365, 1.98] m
Right camera position	[1.0, 0.787, 1.98] m

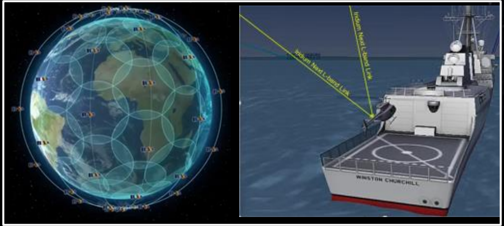
IMU: Modeled with additive white Gaussian noise (AWGN)

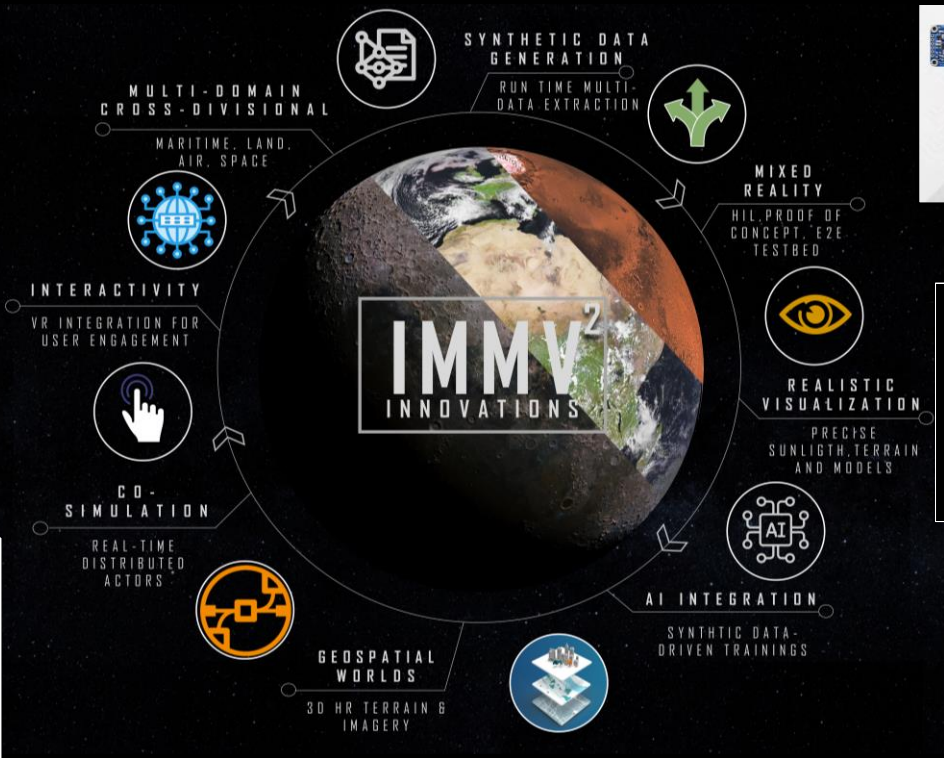
Enconder Model: Angular velocities of all wheels are read directly from UE, where they are affected by slippage due to simplified physical interactions between the wheels and the lunar terrain.

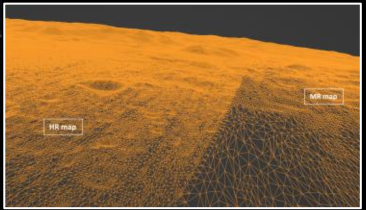
The Interactive Mission Modeling, Visualization & Validation Tool (1/3)



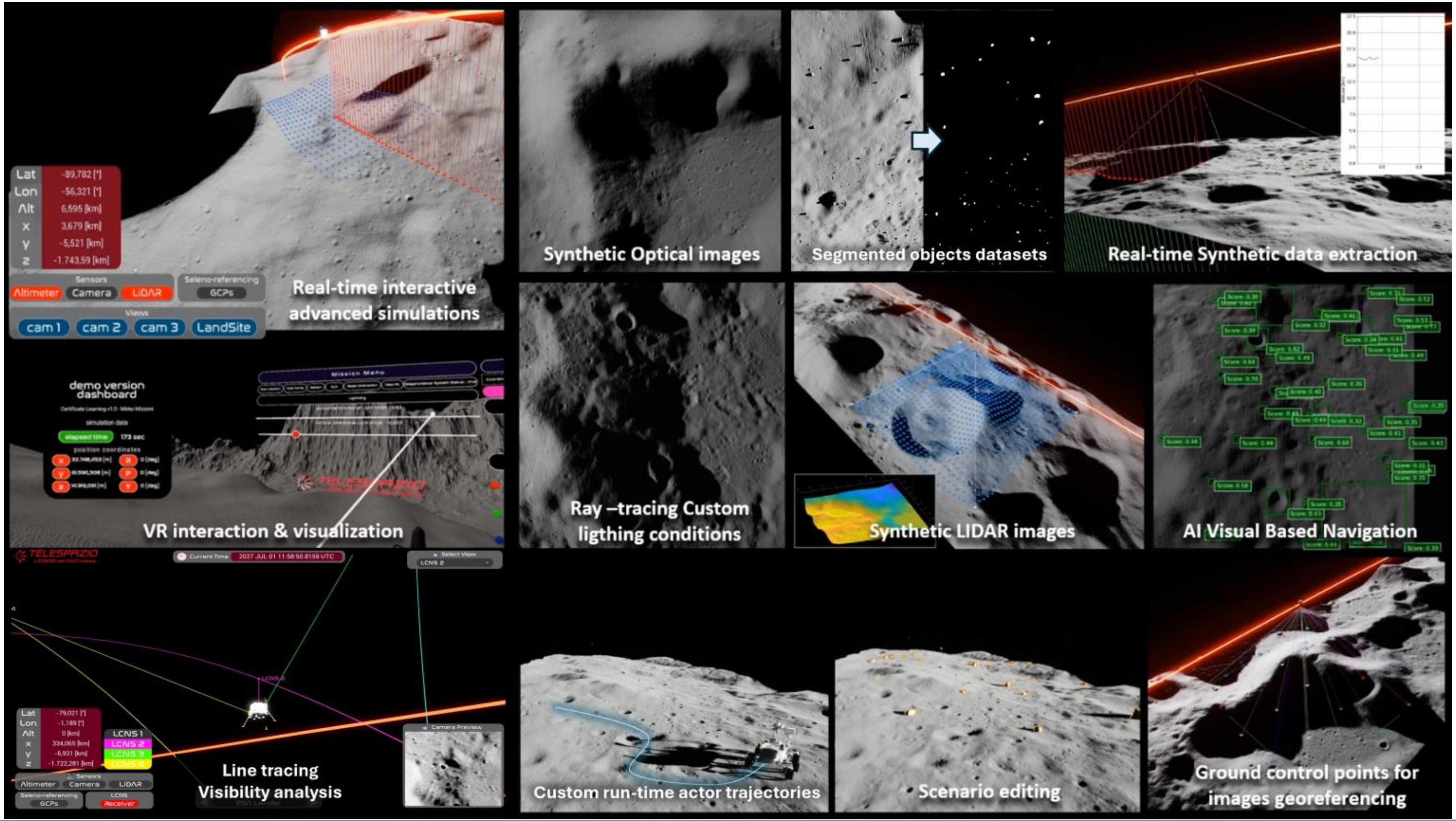




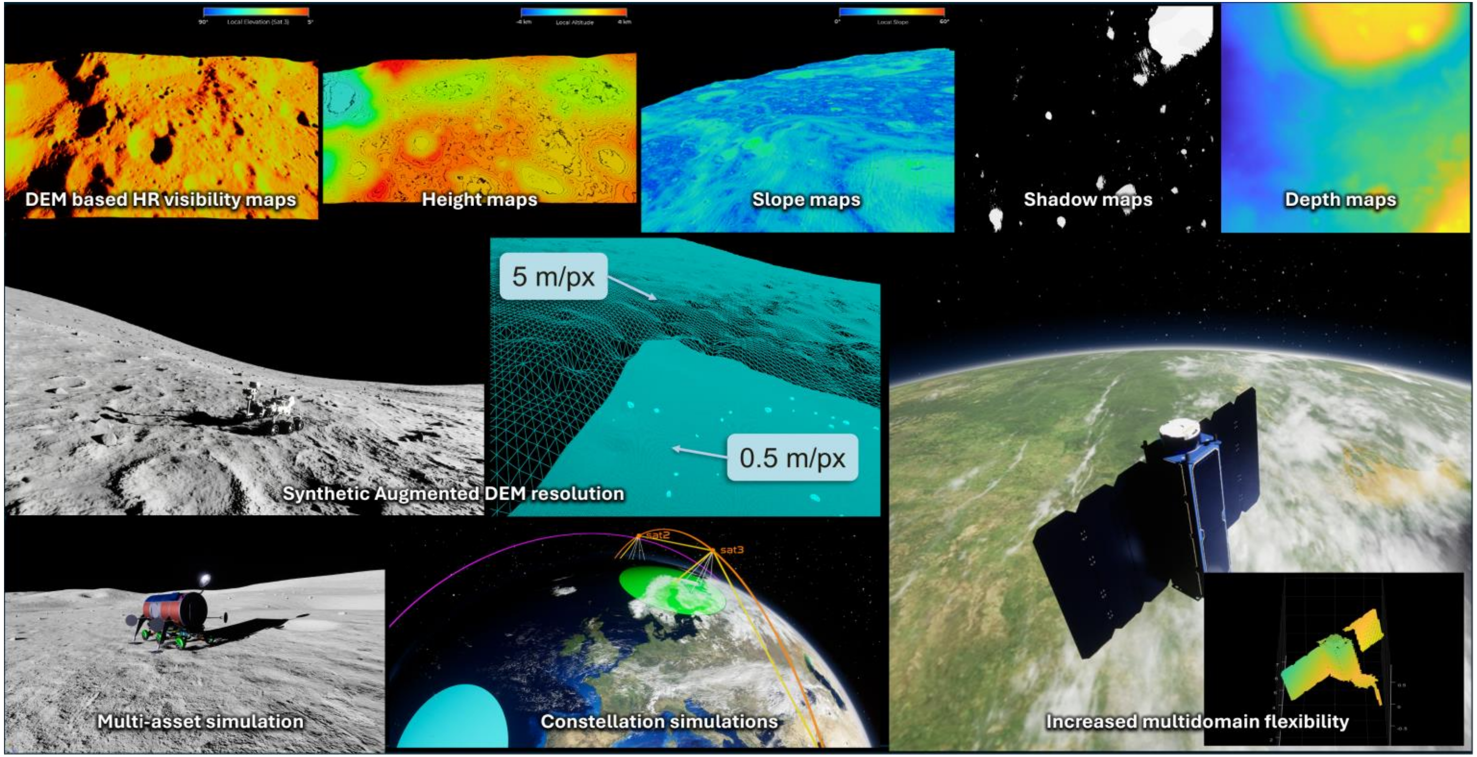




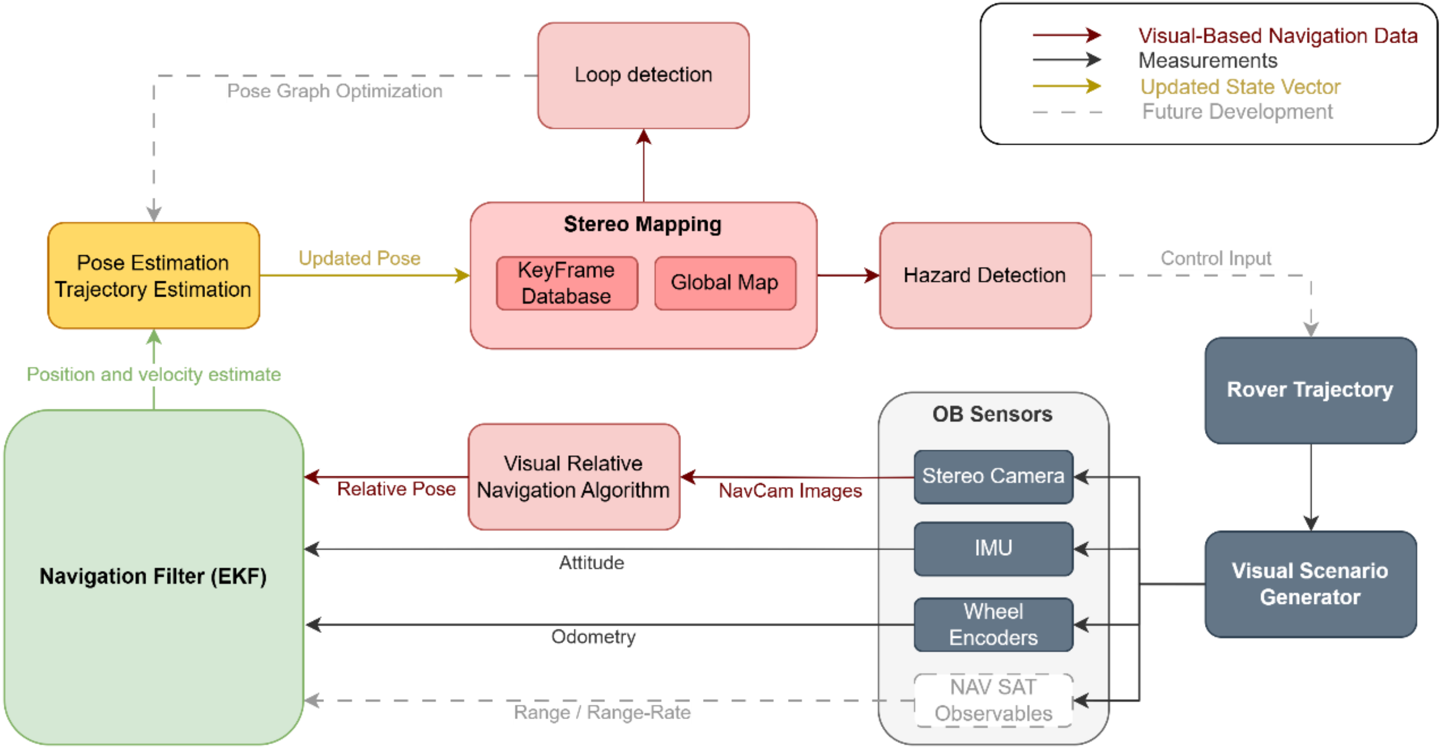
The Interactive Mission Modeling, Visualization & Validation Tool (2/3)



The Interactive Mission Modeling, Visualization & Validation Tool (3/3)

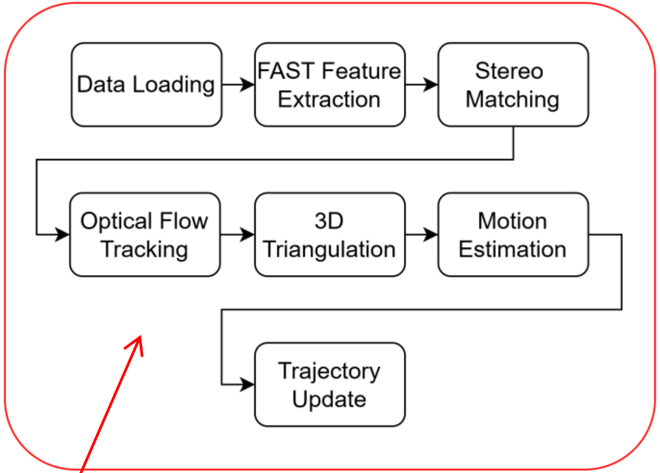


Multi-Sensor Fusion Functional Architecture



Visual Based Navigation - Relative Navigation

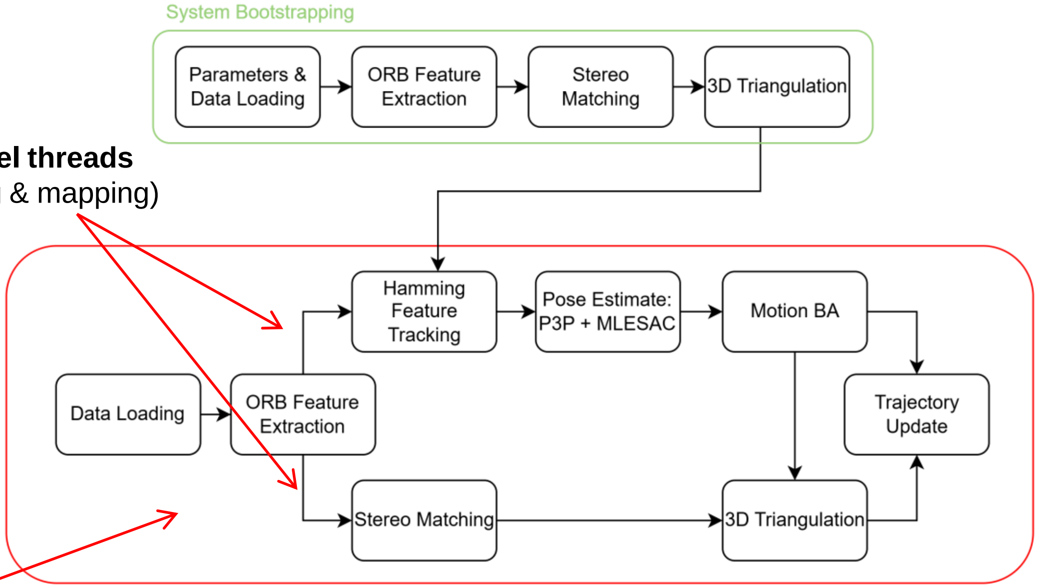
First Approach



Designed using lightweight methods
(FAST, LK optical flow, SGBM)

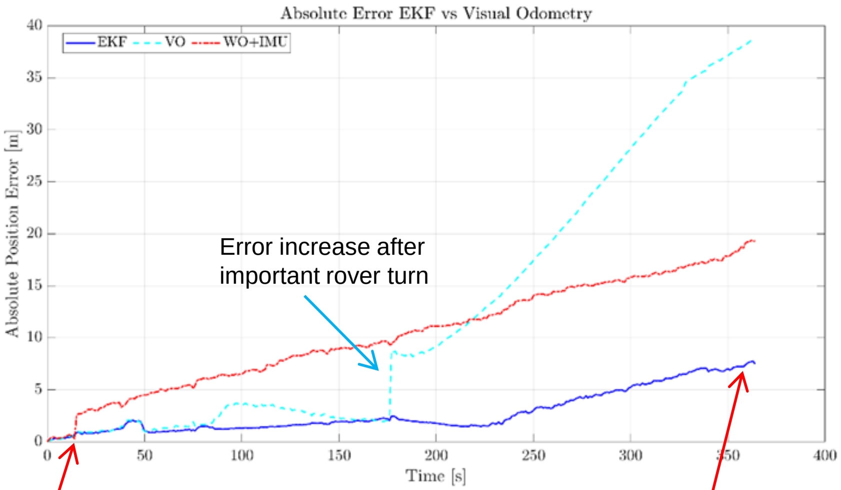
Second Approach

Parallel threads
(tracking & mapping)



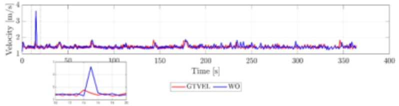
More complex but more accurate (in the reference trajectory VO accuracy improved by 0.6%)

Results - First Visual Relative Localization Algorithm

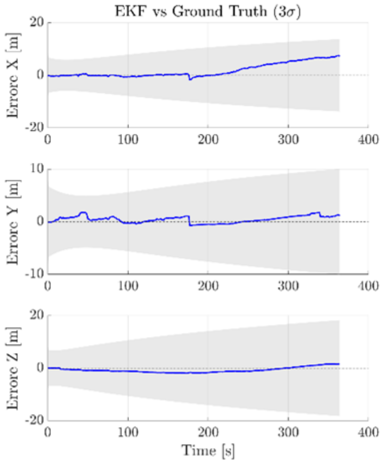


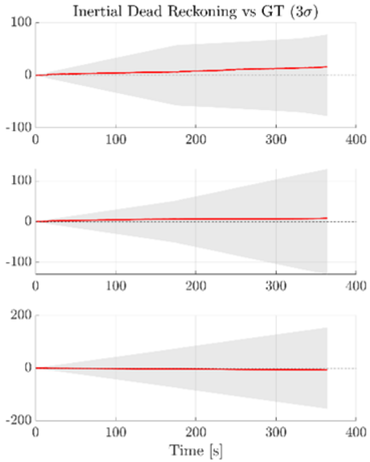
Error increase after important rover turn

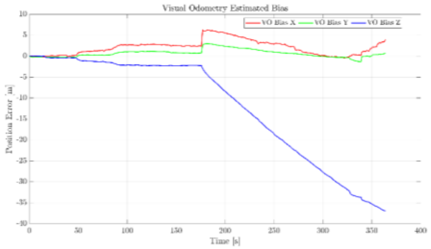
Wheel slippage erroneous reading

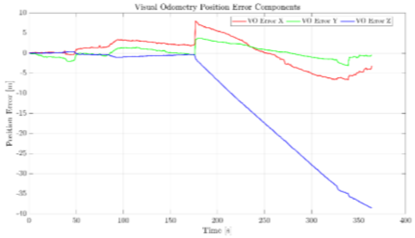


7.6 meters of absolute error (about 1.5% of the distance)



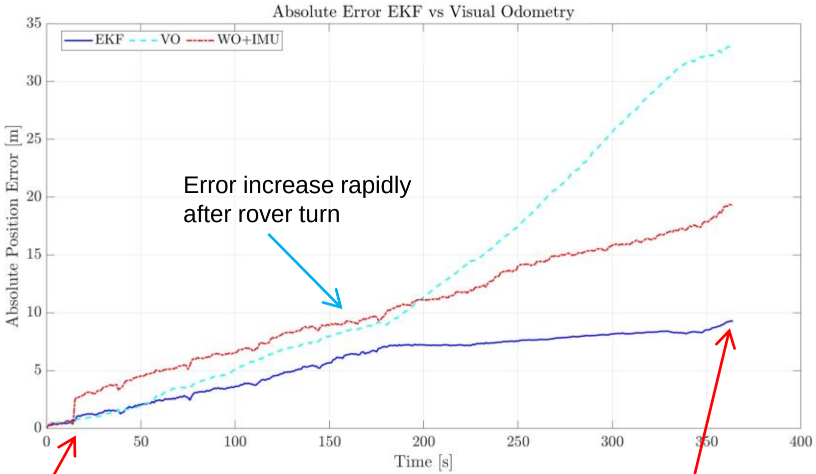




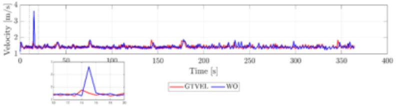


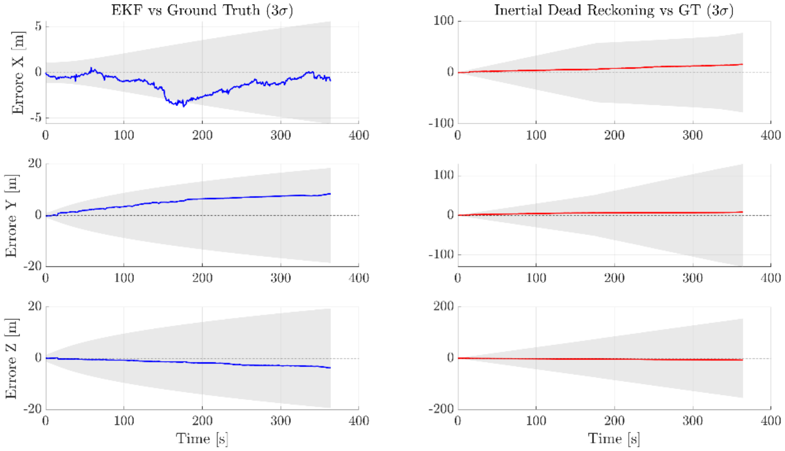
Good consistency over the entire 500 m reference trajectory

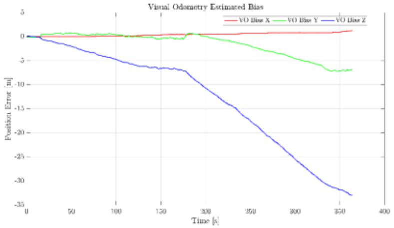
Results - Second Visual Relative Localization Algorithm

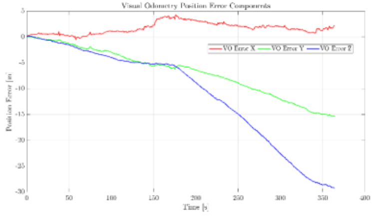


Wheel slippage erroneous reading





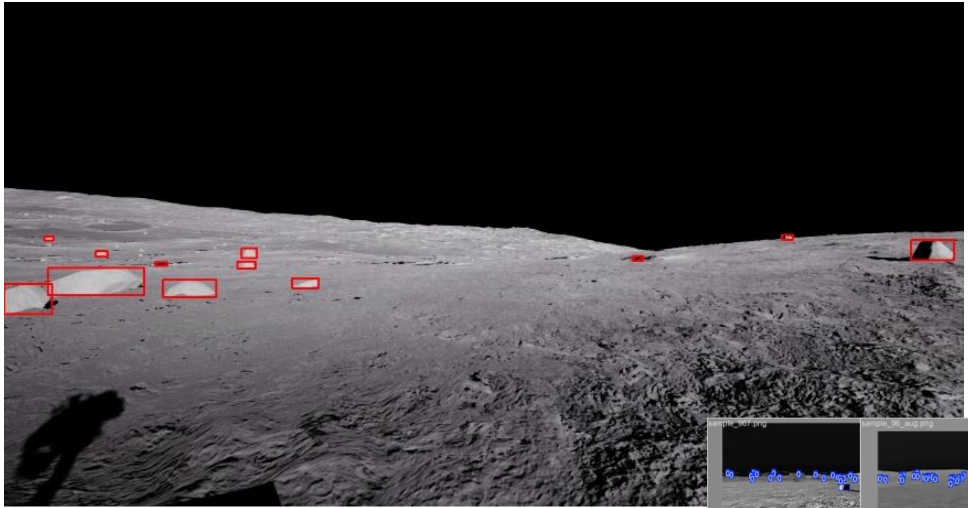




About 9 meters of absolute error (about 1.8% of the distance)

Greater uncompensated drift, particularly in the lateral (Y) direction

Hazard Detection

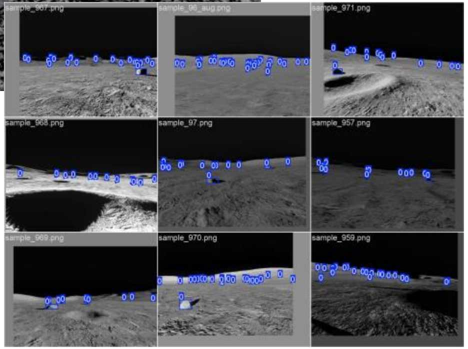


YOLO11s model finetuned using a dataset of 3315 images **synthetically generated** and **automatically labeled** by the **IMMV²**

Larger bounding boxes selected and their centers triangulated to identify locations of rocks

Robust performances both in the testing dataset and in the rover simulation

Metrics	Value
mAP-50	82,85%
mAP-50-90	53,11%
Box Precision	84,55%
Box Recall	71,34%



Dataset Preprocessing:
Illumination normalization
Removal of small rock labels (size <5 pixels)

Fine-tuning:
10 epochs
Batch size: 9
Input resolution: 1280 px

Conclusions & Next Step

Conclusions:

- **Multi-sensor fusion approach** for rover navigation on the lunar surface, evaluating the performance of **two VBN pipelines** integrated with synthetic wheel odometry and inertial measurements through EKF
- The **second algorithm** achieved improved pure visual odometry performance but exhibited reduced correction efficacy when fused in the EKF, resulting in **greater uncompensated** drift, particularly in the lateral (Y) direction
- Conversely, the **first algorithm** showed slightly lower VO accuracy but benefitted more substantially from the EKF's state estimation and bias correction, leading to **improved global localization accuracy** over the entire 500 m reference trajectory
- The resulting maximum position error was constrained within **7.5 m**, corresponding to 1.5% of the total travelled distance.

Next Step:

- **NAV SATs observables** will be integrated in the pipeline to analyze the improvement introduced by a navigation constellation around the moon;
- **Loop closure detection** and global pose graph optimization will be integrated to further suppress accumulated drift, particularly in **longer traverses;**
- **Autonomous path planning** and **decision-making modules** will be introduced to enable dynamic interaction with the IMMV2 simulator through bidirectional control of navigation and hazard avoidance

Thank you
for your attention

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