Stereo and Monocular Vision Guidance for Autonomous Aerial and Ground Vehicles

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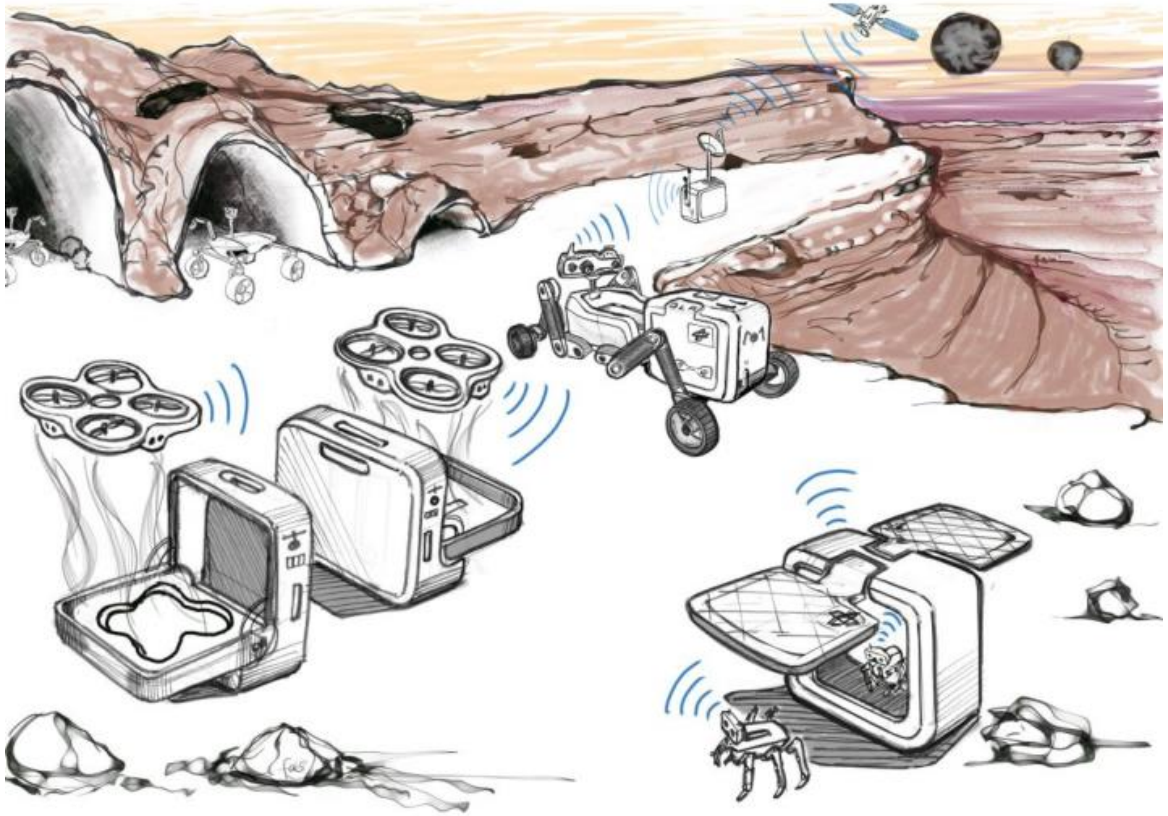
13/09/2019, Padova

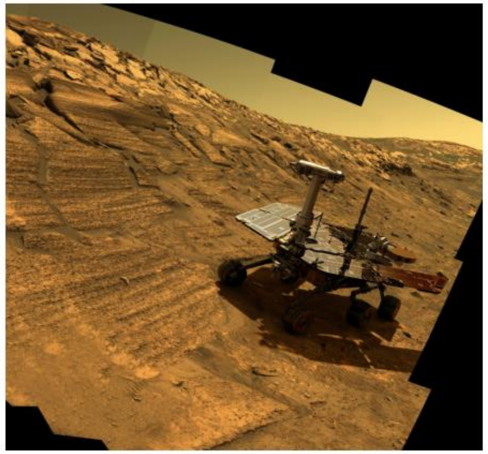
Context: Heterogeneous agents for space exploration



Artistic impression of a multi-agent exploration scenario (*image courtesy of DLR – Robotics and Mechatronics Center*)

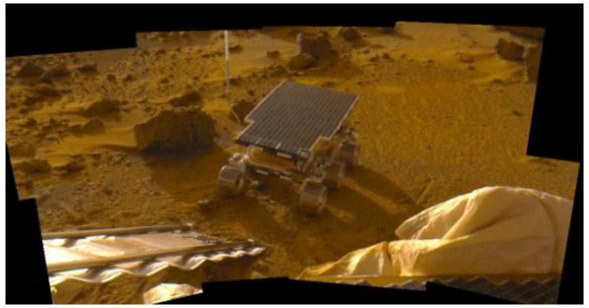
- Robotic explorers increase the return of exploration missions thanks to *in-situ* operations
- Future planetary exploration involves *cooperation* between heterogeneous agents (ground + aerial)
- Ground agents can operate for prolonged sessions and carry heavy instruments for atmosphere and ground analysis
- Aerial agents can perform reconnaissance tasks and long distance scouting to detect targets of scientific interest
- Higher and more efficient coverage

Unmanned exploration of Mars



(a) Opportunity

(b) Curiosity



(c) Sojourner

(d) Mockups of each rover compared

Current planetary exploration belongs to ground rovers:

- **Sojourner** (1997): wheel odometry + gyro for localization. Cameras only for scientific purposes
- **MER** (2004): Full on-board stereo Visual Odometry -> avoid localization drift from wheel slippage. Performed for short periods to avoid excessive CPU load
- **MSL** (2011): More powerful hardware allows S-VO for longer periods. 3D mapping for hazard detection. Autonomous activation of S-VO when needed.

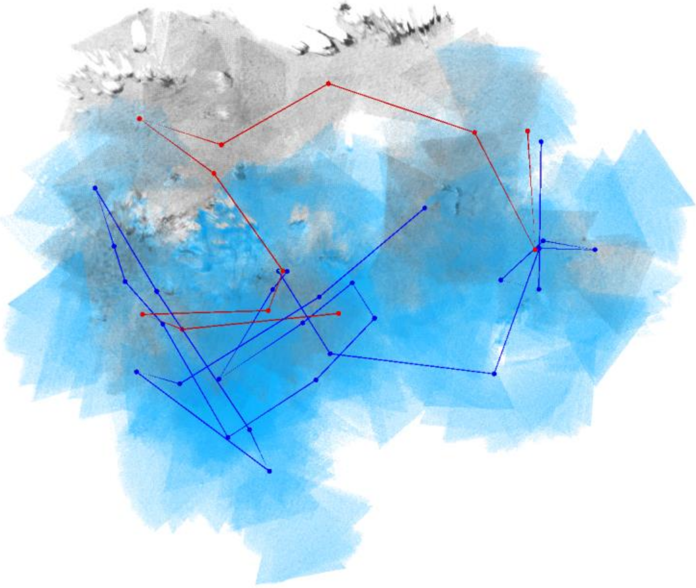
Long-term mapping for stereo vision systems

Up to now:
- Rovers employ stereo Visual Odometry for navigation during traverses -> *dead-reckoning* still subjected to drifts
- Global localization absent or relying on orbiters

First major research objective:

Development of a re-localization algorithm to perform *place recognition* and *loop closure:*

- Targeted at ground vehicles equipped with stereo cameras
- Enables localization across multiple mapping sessions
- Allows to share exploration targets across multiple agents to maximize coverage
- Suitable for resource-constrained computing platforms and challenging natural environments



Automatically merged maps from the LRU (Lightweight Rover Unit) and LRU2 rovers on Mount Etna

Vision-based navigation for aerial agents

Why UAVs for planetary exploration?

- Not constrained by ground traversability
- Can expand the perception range of ground vehicles
- Light vehicle by design, suitable to be deployed in swarms!

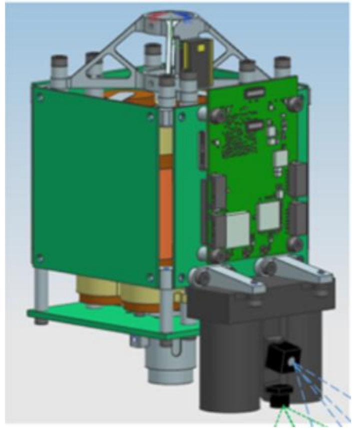
Autonomous UAV operations are challenging:

- Need real-time (10 – 30 Hz) high-level trajectory instructions
- Path planning requires position and velocity estimates -> Visual Odometry
- Mass+Power constraints & rad-hard hardware affect computational performances

Challenging perception systems:

- UAVs prefer *monocular* vision systems
    - Constrained resources -> hard to process high-freq stream of stereo data
    - Reduced stereo baseline -> degenerates to monocular vision

NASA Mars Helicopter Scout: first *soon-to-fly* planetary aerial explorer



NASA Mars Helicopter Scout, sensor assembly. Monocular vision setup (2° camera only for sporadic hi-res images, not used for navigation) [1]

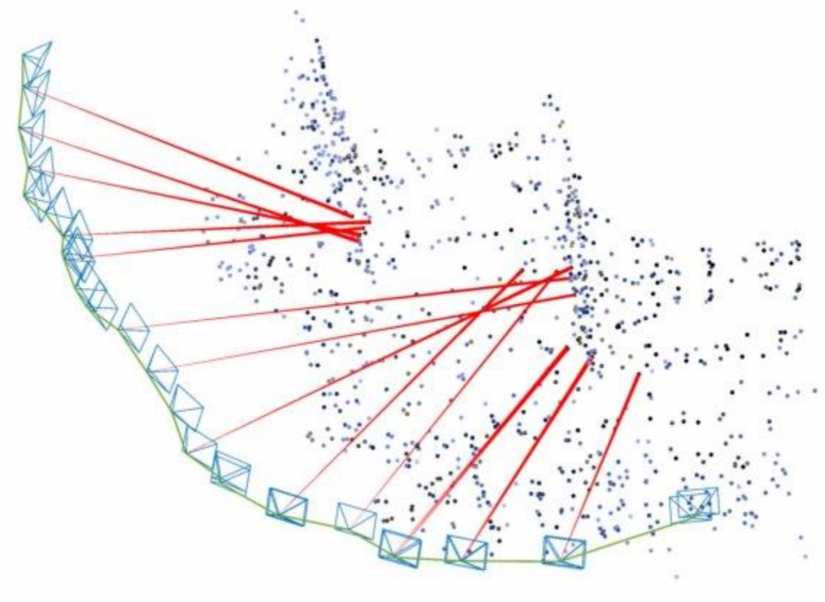
[1] J. Balaram et al. *Mars Helicopter Technology Demonstrator,* AIAA SciTech Forum 2018

Vision-based navigation for aerial agents

Problem! Monocular perception loses **scale** information.

Second major research objective:

- Development of a scale-aware fast monocular Visual Odometry algorithm suitable for UAV navigation
- Traditionally scale is obtained by integrating accelerations. However:
    - Measurements of accelerations are noisy
    - IMU & monocular vision fusion is delicate. Suffers from extrinsic mis-calibrations and convergence in initialization not guaranteed! [2]
- We propose to retrieve scale using low resolution range sensors
    - Direct depth measurements
    - Low power / mass sensors



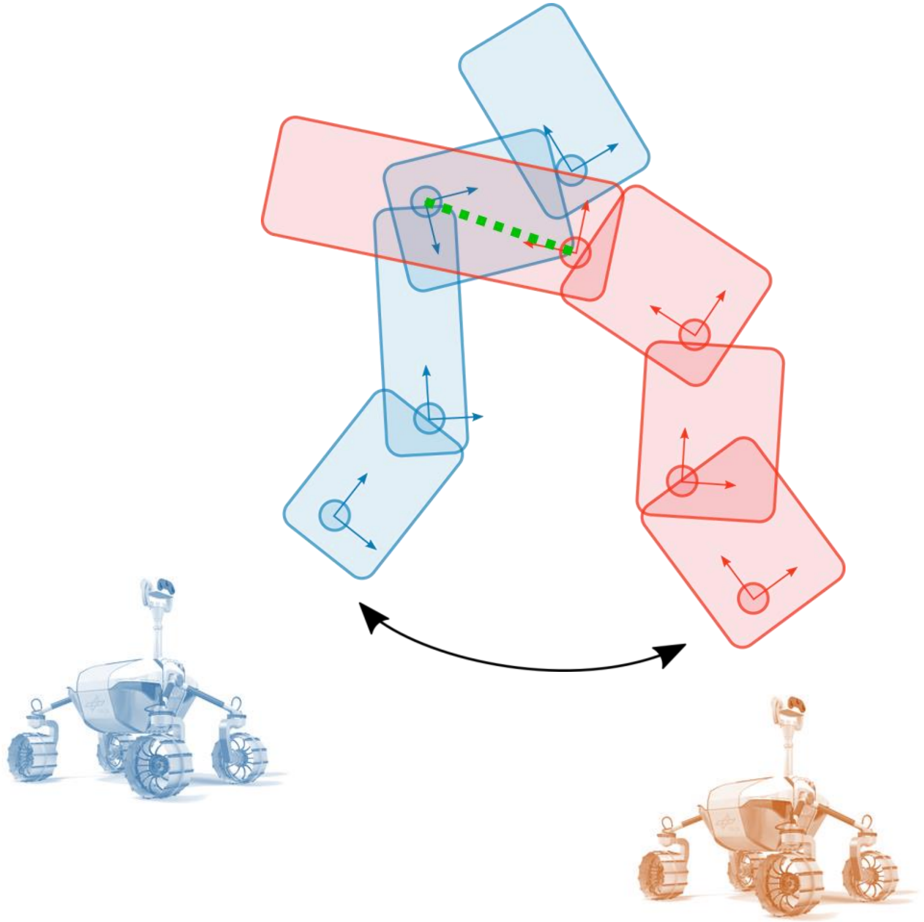
Camera poses, 3D landmarks and range measurements in a correctly scaled monocular reconstruction [3]

[2] Lee S. and De Croon, *Stability-based Scale Estimation in Monocular SLAM,* Robotics and Automation Letters, 2018
[3] Giubilato R. et al, *Scale Correct Monocular Visual Odometry using a LiDAR Altimeter,* IEEE/RSJ International Conference on Intelligent Robots and Systems, 2018

Relocalization on Submaps: Multi-session Mapping for Planetary Rovers Equipped with Stereo Cameras*

- Each rover perform Stereo Visual Odometry for localization
- Map building using the *submap* paradigm: local pointclouds referred to the session origin from their local reference system

To enable multi-session mapping we propose a *fast relocalization scheme* to compute $\mathbf{T}_{1,2}$



* In review for Robotics and Automation Letters + IEEE International Conference on Robotics and Automation, 2020

Scale-aware Monocular Visual Odometry using Low Resolution Range Sensors*

Sensor fusion between low-res range sensors and monocular vision for:
- Recovering absolute scale
- Constrain scale drift relying on background optimization

This research objective is achieved in **two steps**:
- Algorithm prototype to assess the feasibility of integrating low res sensors
  - No real-time constraints
  - Usage of a time-of-flight camera of 8x8 pixels (64 range measurements)
  - Comparison with higher accuracy / mass 2D LiDAR sensors

- «Fly-ready» monocular Visual Odometry
  - Real-time constraints (30Hz pose estimates)
  - 1D LiDAR altimeter (1 range measurement only)
  - Comparison with D-GPS ground truth

* Chiodini S., Giubilato. R, et al. Retrieving Scale on Monocular Visual Odometry Using Low Resolution Range Sensors, in review for IEEE Transaction on Instrumentation and Measurements
Chiodini S., Giubilato. R, et al. Monocular visual odometry aided by a low resolution time of flight camera, IEEE Workshop on Metrology for Aerospace, 2017

Monocular VO + ToF fusion – General Pipeline

Overview of the pipeline:

- Inputs are monocular images and range measurements
- A *front-end* matches 2D image features (SURF) across a windows of 5 frames.
- Triangulated points are used to localize the camera for the next incoming frames
- Range measurements are associated to image features to establish **scale constraints**
- A window of 15 frames is processed by an optimization **back-end** which optimizes camera positions and landmark coordinates

Range fusion

Range measurements are associated to visual information in 2 ways:

- On the ***image* space**: range measurements are *projected* in the images and tracked using *optical flow*. The triangulated point from each range feature track is compared with the range measurements, obtaining a *scale factor*
- On the ***3D space***: range measurements are considered as 3D points in front of the respective cameras. Map landmarks in close proximity are searched for and associated. Measured depths and landmark depths establish range constraints

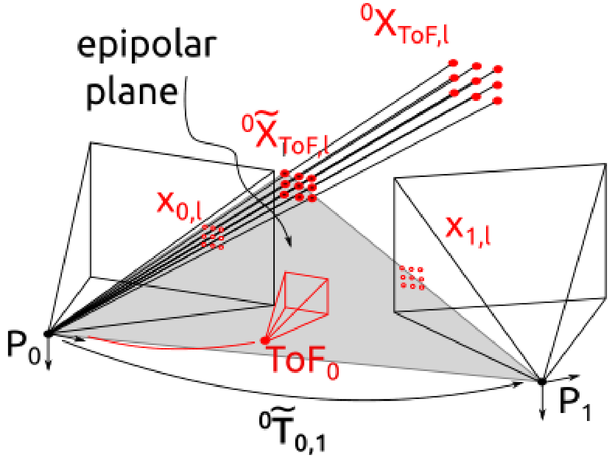
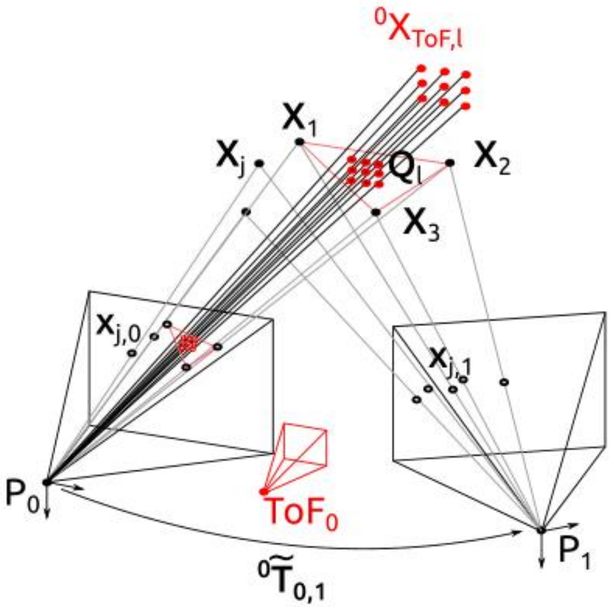


Image space

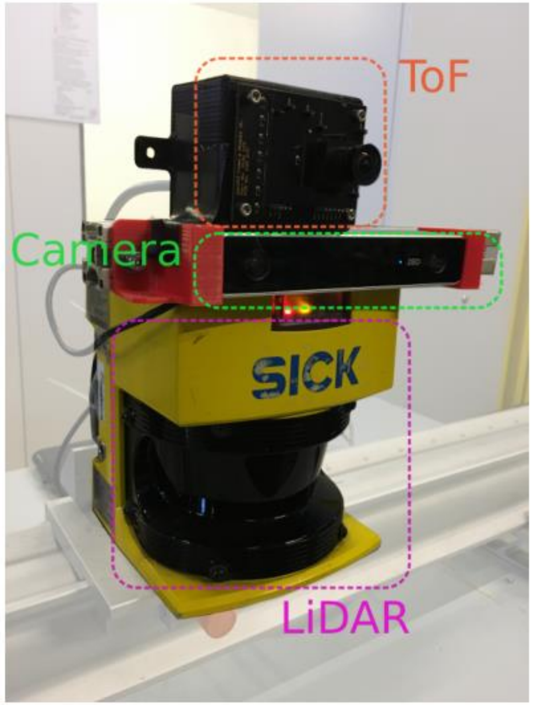


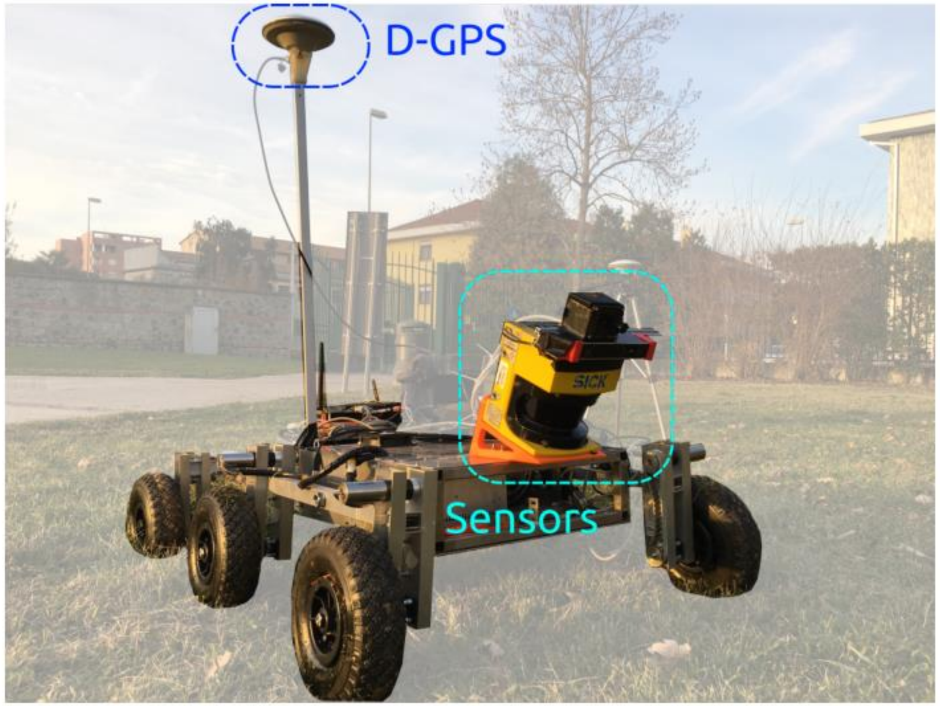
3D space

Sensor setup

The test setup comprises:

- Stereo camera (left images for monoVO, stereo for comparison)
- ToF camera (64 ranges in 8° FoV)
- 2D LiDAR (360 ranges in 180° planar FoV, for evaluation with a more precise depth sensor)
- D-GPS for outdoor ground truth





Tested with our MORPHEUS mobile robotic platform instead of an UAV
-> LiDAR is 5kg!

Extrinsic calibration

To refer range measurements to the camera reference frame:

- *Extrinsic* calibration. Output is a 6DoF Transformation

For the setup Monocular + ToF camera no published work is available.
We propose a calibration pipeline:

- Observe a corner in various positions (n>6 for 6 DoF)
- Detect corner in RGB and range images
- Establish *reprojection* constraints
- Solve for T_{cam}^{ToF}

Scale Correct Monocular Visual Odometry Using a LiDAR Altimeter*

- Camera-Range sensor fusion approach validated in previous section

New objectives:

- Real-time implementation
- Minimalistic range setup, 1 range measurement from LiDAR altimeter
- Optimize for scale in back-end
- Multi-threaded architecture
- ROS (Robot Operating System) C++ interface
- Evaluation on ad-hoc experimental system + novel extrinsic calibration procedure

* Giubilato. R. et al, Scale Correct Monocular Visual Odometry Using a LiDAR Altimeter, IEEE/RSJ International Conference on Intelligent Robots and Systems, 2018

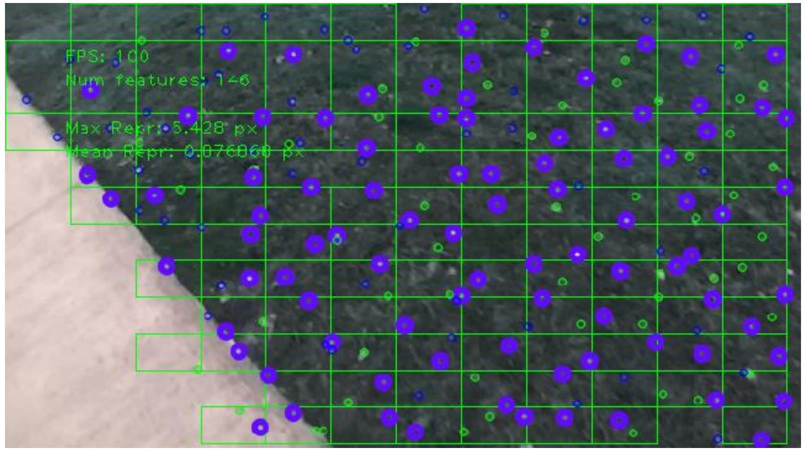
Algorithm overview

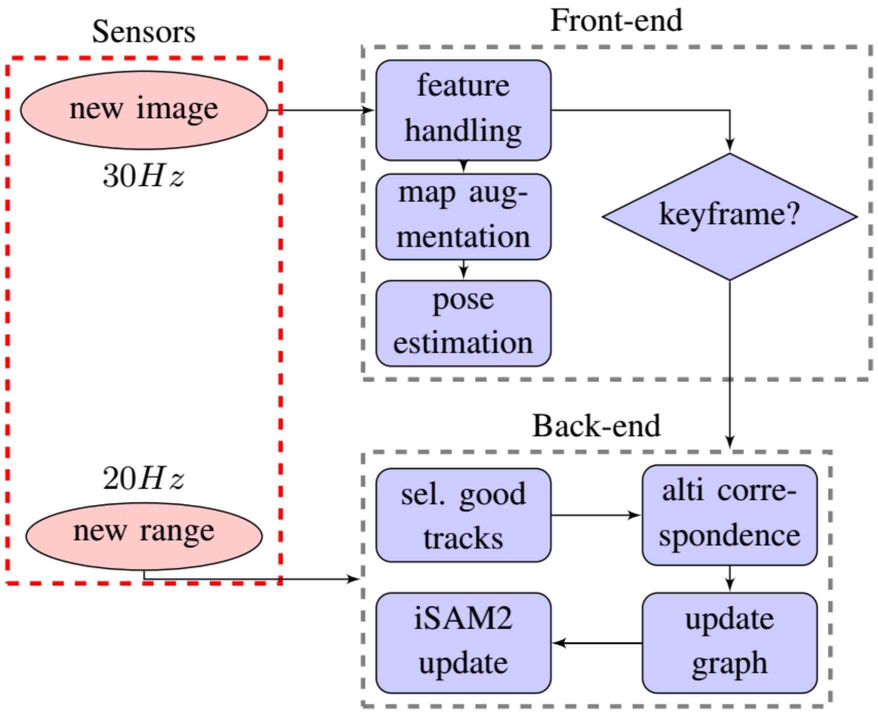
Front end:

- FAST feature detection and bucketing (strongest metric per grid cell)
- Pyramidal Lukas Kanade *optical flow* tracker instead of complex feature matching

Keyframe selection:

- Euclidean distance threshold from last KF pose
- Percentage of lost tracks
- Store most recent range measure in current KF (for *back-end* optimizer)

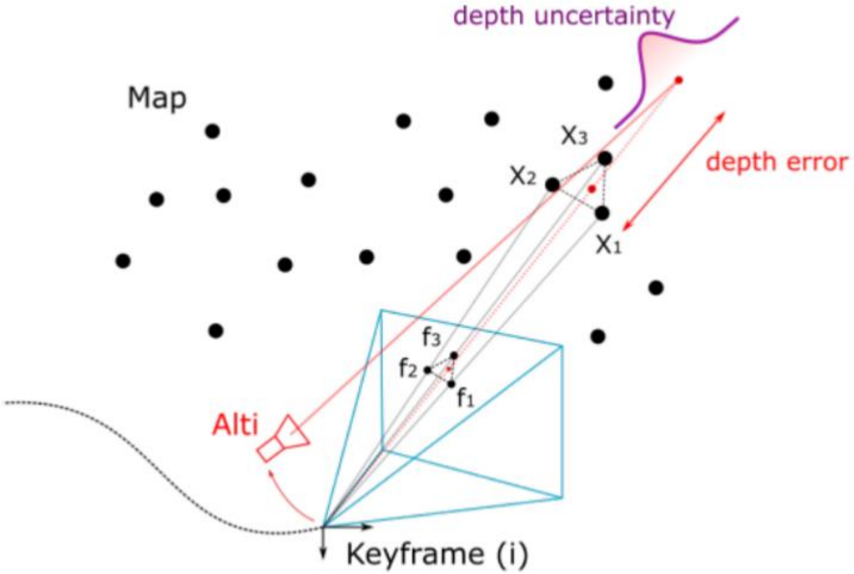




Range – Landmark association

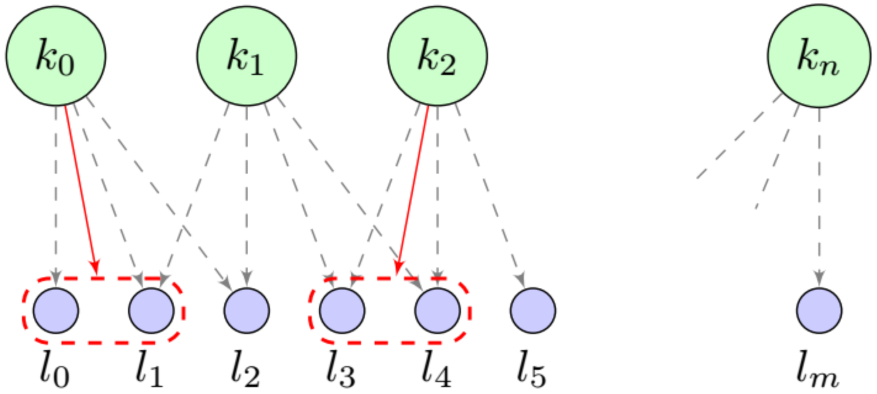
Altimeter association:

- When a keyframe is created, the range measure (3D point) is projected in the image plane
- Neighbor features are selected if nearer than a threshold
- Association established if {X1, X2, X3} are locally planar to avoid false depth constraints



Optimization backend:

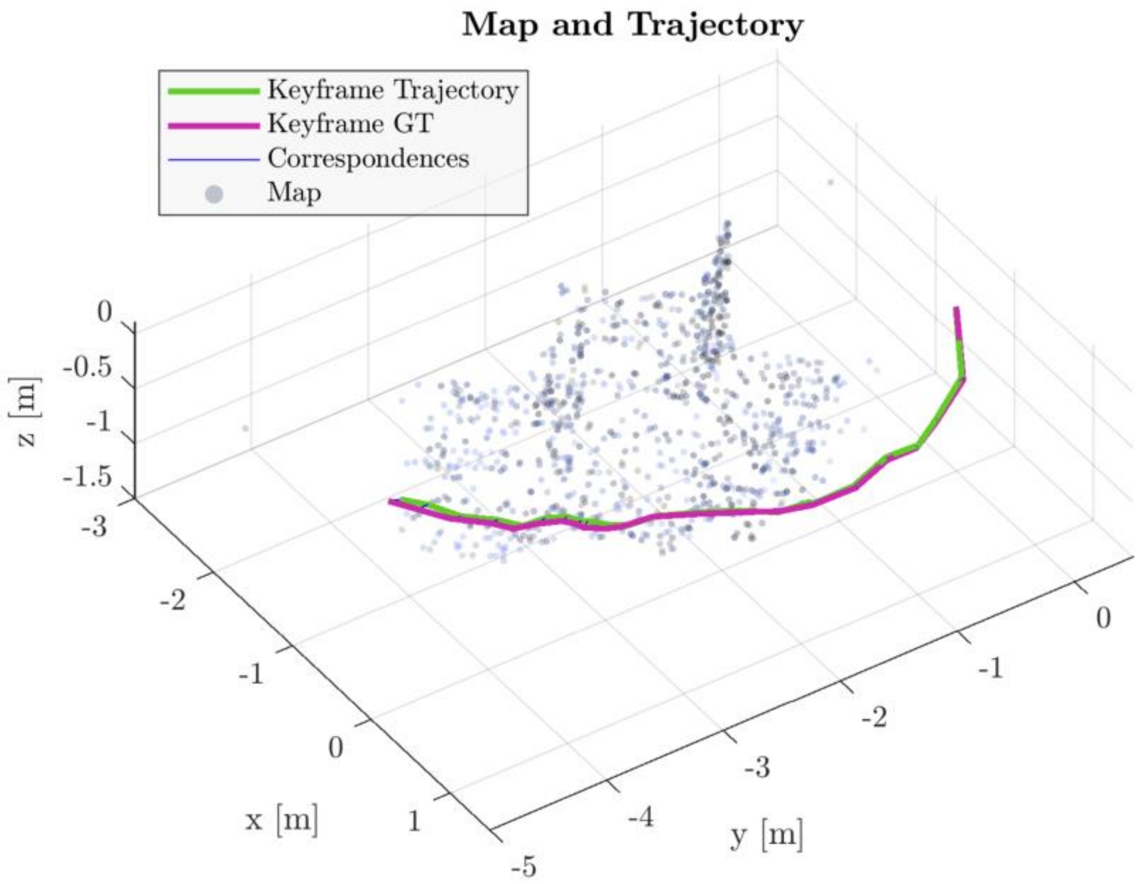
- We build a factor graph using the iSAM2 smoother
- Altimeter measures constrains the neighbor landmarks depth with respect to the considered keyframe pose
- The authority of iSAM2 updates depend on the uncertainty of range measurements



TUM RGB-D Dataset results

Tests using the TUM (Technische Universitaet Munchen) Dataset:

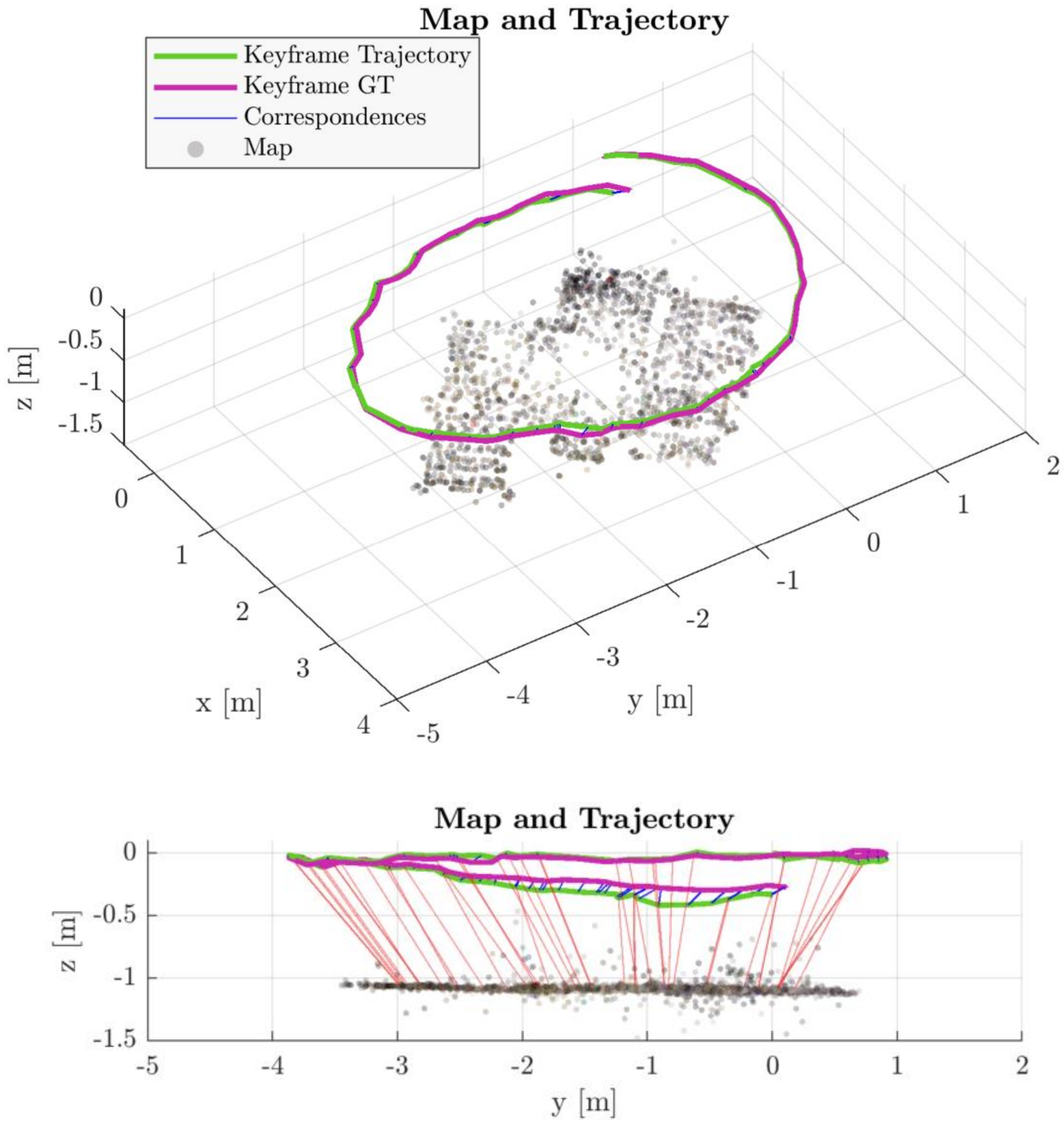
- Keeping central pixel in the depth images for simulating altimeter measurements
- Outperforms RGBD-SLAM



TUM RGB-D Dataset results

Tests using the TUM (Technische Universitaet Munchen) Dataset:

- Comparable performances to state-of-the-art stereo and RGB-D SLAM systems!
- Outperforms RTAB-MAP



Outdoor tests + D-GPS

Tested in outdoor scenarios with custom experimental setup. 3 Sequences with different motion types:

- Hovering
- Closed loop
- Landing

Thank you for listening!
Questions?

Publications

Journals

- **R. Giubilato**, S. Chiodini, M. Pertile e S. Debei, «An evaluation of ROS-compatible stereo visual SLAM methods on a nVidia Jetson TX2,» *Measurement,* vol. 140, pp. 161 - 170, 2019.
- M. Pertile, S. Chiodini, **R. Giubilato**, M. Mazzucato, A. Valmorbida, A. Fornaser, S. Debei e E. Lorenzini, «Metrological Characterization of a Vision-Based System for Relative Pose Measurements with Fiducial Marker Mapping for Spacecrafts,» *Robotics,* vol. 7, n. 3, p. 43, 2018.
- S. Chiodini, M. Pertile, **R. Giubilato**, F. Salvioli, M. Barrera, P. Franceschetti e S. Debei, «Experimental evaluation of a camera rig extrinsic calibration method based on retro-reflective markers detection,» *Measurement,* vol. 140, pp. 47-55, 2019.

Conference Proceedings – International

- **R. Giubilato**, S. Chiodini, M. Pertile e S. Debei, «Scale Correct Monocular Visual Odometry Using a LiDAR Altimeter,» in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2018
- **R. Giubilato**, S. Chiodini, M. Pertile e S. Debei, «An experimental comparison of ros-compatible stereo visual slam methods for planetary rovers,» in *2018 5th IEEE International Workshop on Metrology for AeroSpace (MetroAeroSpace)*, 2018
- **R. Giubilato**, S. Chiodini, M. Pertile e S. Debei, «Stereo visual odometry failure recovery using monocular techniques,» in *2017 IEEE International Workshop on Metrology for AeroSpace (MetroAeroSpace)*, 2017.
- S. Chiodini, **R. Giubilato**, M. Pertile e S. Debei, «Monocular visual odometry aided by a low resolution time of flight camera,» in *2017 IEEE International Workshop on Metrology for AeroSpace (MetroAeroSpace)*, 2017.
- S. Chiodini, M. Pertile, **R. Giubilato**, F. Salvioli, D. Bussi, M. Barrera, P. Franceschetti e S. Debei, «Rover Relative Localization Testing in Martian Relevant Environment,» in *2019 IEEE International Workshop on Metrology for AeroSpace (MetroAeroSpace)*, 2019.
- M. Pertile, S. Chiodini, **R. Giubilato** e S. Debei, «Calibration of extrinsic parameters of a hybrid vision system for navigation comprising a very low resolution Time-of-Flight camera,» in *2017 IEEE International Workshop on Metrology for AeroSpace (MetroAeroSpace)*, 2017.

Publications

- M. Pertile, S. Chiodini, **R. Giubilato**, M. De Cecco e S. Debei, «Position Measurement and Uncertainty Analysis for the Shutter Mechanism Mounted on the Rosetta Mission,» in *2018 5th IEEE International Workshop on Metrology for AeroSpace (MetroAeroSpace)*, 2018.

Conference Proceedings – National

- **R. Giubilato**, S. Chiodini, M. Pertile e S. Debei, «Extrinsic Calibration of a Stereo Camera and 2D LiDAR Setup,» in *II Forum Internazionale delle Misure*, 2018
- S. Chiodini, M. Pertile, **R. Giubilato**, F. Salvioli, M. Barrera, D. Bussi, P. Franceschetti e S. Debei, «Uncertainty Evaluation of a Visual Odometry Algorithm for Martian Environments,» in *III Forum Internazionale delle Misure*, 2019.
- M. Pertile, M. Mazzuccato, G. Pastore, A. Valmorbida, S. Chiodini, **R. Giubilato**, S. Debei e E. Lorenzini, «Comparison of Vision System Approaches for Distance Measurement of a Tether Tip Mass During Deployment on High Eccentricity Orbit,» in *I Forum Internazionale delle Misure*, 2017
- S. Chiodini, **R. Giubilato**, M. Pertile e S. Debei, «Experimental Evaluation of a Monocular Visual Odometry System Aided by a Time of Flight Camera, Comparison with a Stereo System,» in *I Forum Internazionale delle Misure*, 2017.