Visual odometry and vision system measurements based algorithms for rover navigation

Request of admission to the final exam

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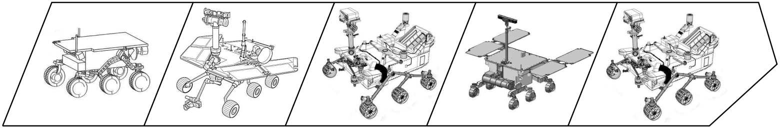
Università degli Studi di Padova

Outline

Space Rovers

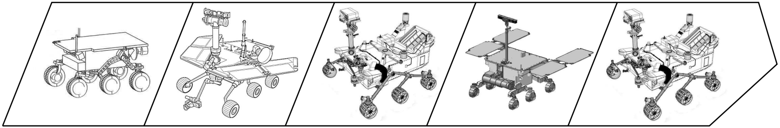
CISAS G. COLOMBO

Università degli Studi di Padova



1996	2003	2011	2020	2020
Mars Pathfinder	**Mars Exploration Rover**	**Mars Science Laboratory**	**ExoMars 2020**	**Mars2020**
2-3 m per sol	100 m per sol	100 m per sol	100 m per sol	more complex tasks
wheel encoders	wheel encoders	wheel encoders	wheel encoders	global rover localization
sun sensor	sun sensor	sun sensor	sun sensor	terrain relative navigation
	IMU	IMU	IMU	
	VO for slip check	VO for slip check and every step	VO for slip check and every step	
		terrain hazards detection	terrain hazards detection	

Space Rovers



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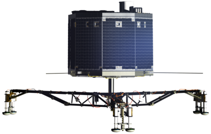
Small bodies exploration

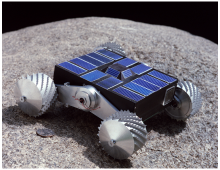
Philae lander

- Payload of ESA's Rosetta spacecraft (2014)
- Designed to land on Comet 67P/Churyumov-Gerasimenko



Nanorover

- Designed by NASA-JPL for Hayabusa mission (2000)
- Project cancelled

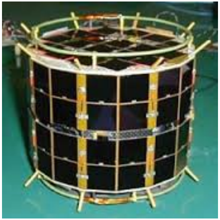


PROP-F

- Payload for Phobos 2 Soviet mission (1988)
- Mission failed

MINERVA

- Payload of JAXA's Hayabusa mission (2003)
- Deployment failed



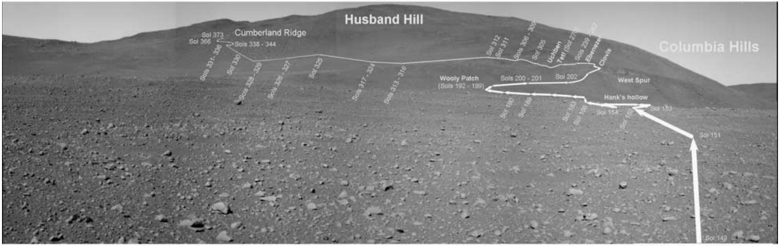
MASCOT

- Payload of JAXA's Hayabusa 2
- Developed by DLR
- Deployment 2019

Background & motivation

- The robot need to know where it is, to go from A to B
- Navigation without hitting obstacles
- Detection of goal location
- With wich accuracy and reliability do we reach the goal?
- Represent the map for the robot and the position of the robot in the map

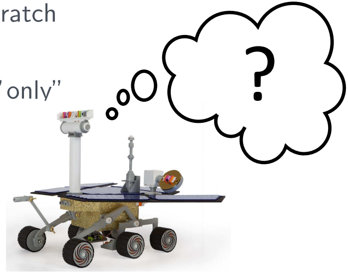
Spirit Rover Traverse (Sol 373)



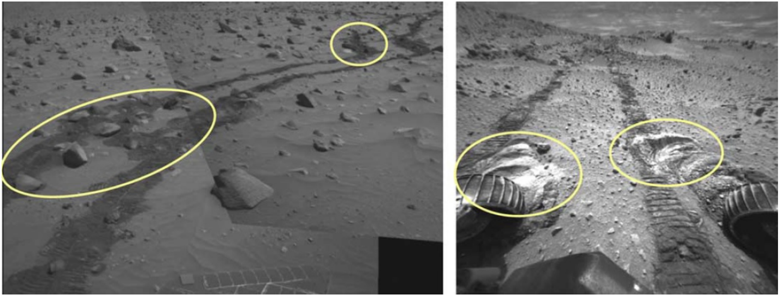
OSU Mapping and GIS Laboratory

Background & motivation

- Global localization
  - The robot is not told its initial position
  - Its position must be estimated from scratch
- Position Tracking
  - A robot knows its initial position and "only" has to accommodate small erros in its odometry as it moves
- How to localize?
  - Localization based on external sensors, landmarks
  - Odometry
  - Map Based Localization (without external sensors or artificial landmarks. Just use robot onboard sensors)

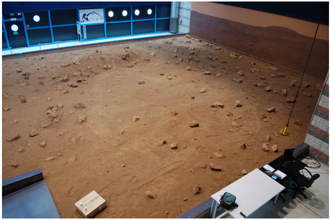


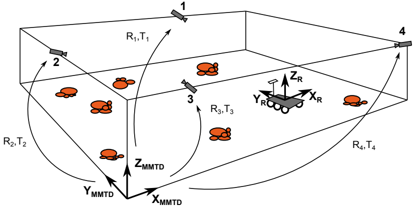
- Advanced space missions require increased autonomy
- No GPS signal on Mars and other small solar system bodies
- Inertial navigation sensors exhibit unacceptable drifts
- Wheel odometry has wide uncertainty due to slippage of wheels on a natural, often sandy or slippery, surface

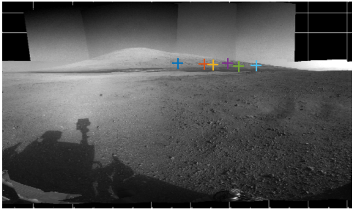


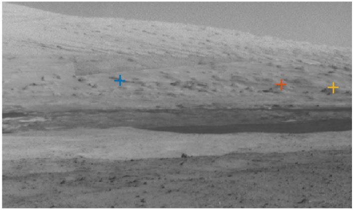
Collaboration with ALTEC

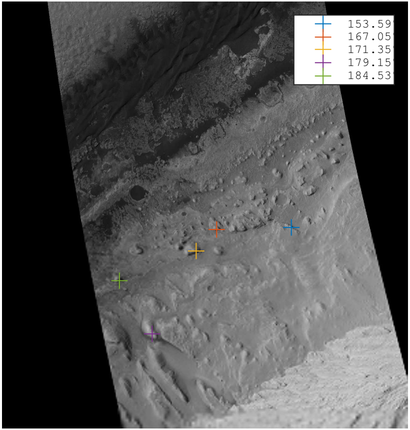
- ExoMars 2020 rover operations will be managed by the Rover Operation Control Center (ROCC), located in ALTEC
- Support to the integration of the Mars Moon and Terrain Demonstrator (ALTEC)
- Global localization studies for operational analysis of ExoMars 2020 rover
- Planetary localization studies for operational analysis of robotic mission (e.g. ExoMars), initialization and revision of path estimation onboard rovers (ALTEC)

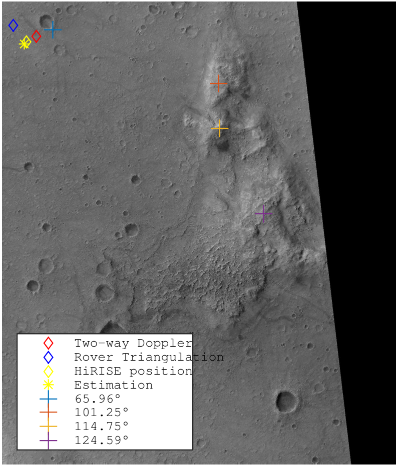


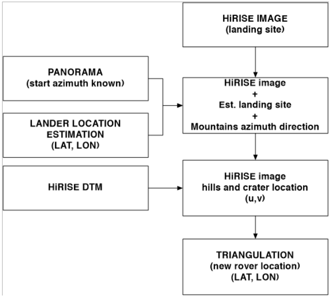







153.59
167.05
171.35
179.15
184.53

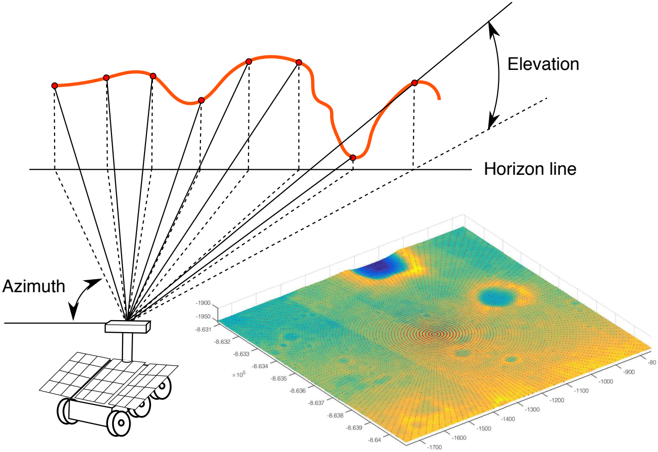




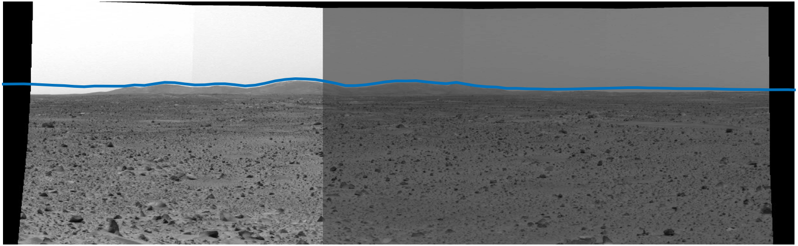
Landing Site	Loc. Error
Spirit	55.55 [m]
Opportunity	546.35 [m]
Curiosity	61.78 [m]

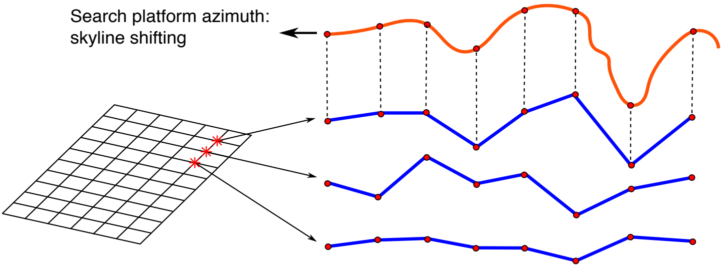
Localization using HiRISE DEM

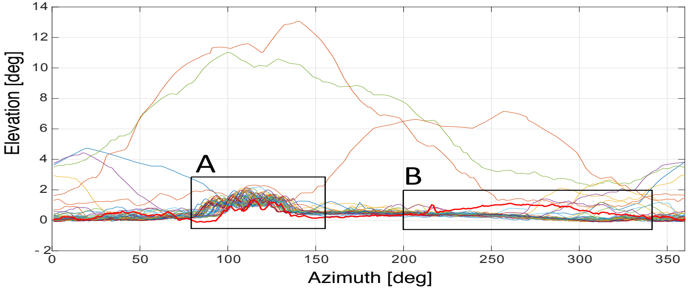
- This algorithm attempts to estimate the position of a rover with a Digital Elevation Model (DEM) and a panoramic image through an exhaustive search

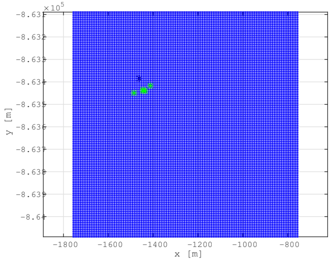


Localization using HiRISE DEM



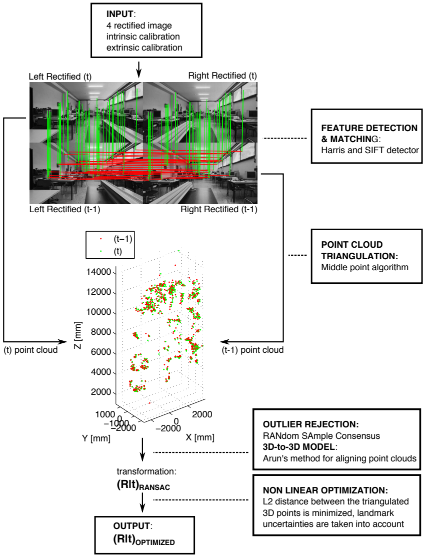






Matching Error	Loc. Error	Azimuth mes.
0.00733 [rad]	51 [m]	90 [deg]
0.00749 [rad]	61 [m]	90 [deg]
0.00752 [rad]	58 [m]	90.5 [deg]
0.00753 [rad]	59 [m]	90 [deg]
0.00759 [rad]	68 [m]	89.5 [deg]

Platform azimuth 91 [deg]



- Stereo camera pose optimization, cost function E_{nl}

$$\mathbf{e}_i = {}^{P1}\mathbf{X}_i - {}^{P1}_{P2}\mathbf{R}\,{}^{P2}\mathbf{X}_i - {}^{P1}\mathbf{t}_{P2,P1}$$

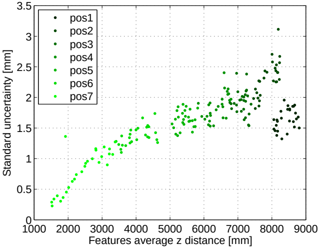
$$\mathbf{C}_i = {}^{P1}\mathbf{C}_i + {}^{P1}_{P2}\mathbf{R}\,{}^{P2}\mathbf{C}_i\,{}^{P1}_{P2}\mathbf{R}^\top$$

$$E_{nl} = \sum_{i=1}^{n} (\mathbf{e}_i^\top \mathbf{C}_i^{-1} \mathbf{e}_i)$$

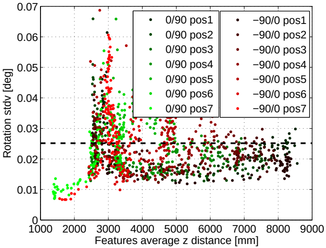
  - ${}^{P1}\mathbf{X}_i$ and ${}^{P2}\mathbf{X}_i$ 3D coordinates of landmark i at time $t-1$ and t
  - $({}^{P1}_{P2}\mathbf{R}|{}^{P1}\mathbf{t}_{P2,P1})$ pose transformationn
  - ${}^{P1}\mathbf{C}_i$ and ${}^{P2}\mathbf{C}_i$ 3x3 covariance matrices of a landmark

- Experimental analysis of how landmark distributions in a scene, as observed by a stereo-camera, affect Visual Odometry measurement performances

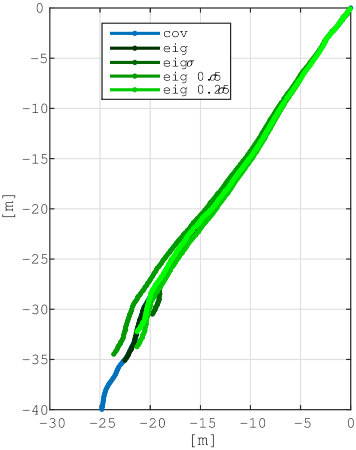
- **Translations**. The step uncertainty is greater when the features are located far away from the camera.

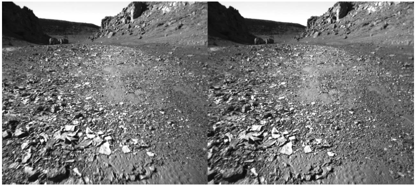


- **Rotations**. The step uncertainty does not grow with the distance from the stereo-camera center.



Visual Odometry a comparison





- **Error 3Dto3D Non linear optimization - 2.04%**
- Error MICP-VO - 0.86% - ICP Stereo Visual Odometry (Jiang et al. 2014)
- Error P3P RANSAC - 2.60% Monocular visual odometry in urban environments using an omnidirectional camera (Tardif et al. 2008)
- Error LIBVISO2 - 4.14% Iterated Sigma Point Kalman Filter in combination with a RANSAC-based outlier rejection (Kitt et al. 2010)

JVSRP Program

- Jet Propulsion Laboratory Visiting Research Student Program (JVSRP)
- Robotic Section - Robotic Mobility (347F) Group supervised by Robert Reid and Issa Nesnas
- Collaboration to develop the navigation system of Hedgehog, a hybrid rover/spacecraft system designed to tumble and hop on asteroids, comets and other small bodies

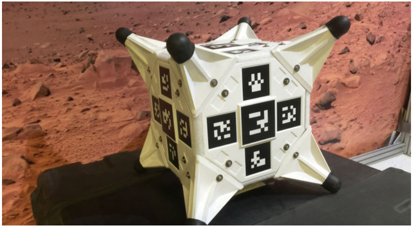
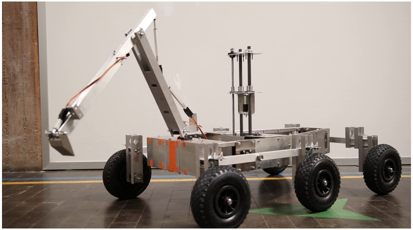


Image credit: NASA/JPL-Caltech/Stanford

Conclusion

- During this Ph.D. work two different global localization framework has been studied and analysed, for two different mission scenario.
- These localization frameworks foreseen a collaborative approach between an orbiter and a daughter rover.
- In the planetary exploration case we have investigated an approach that exploit a Digital Elevation Model, obtained by orbiter images, with surface image captured by the rover. Stereo Visual Odometry algorithms have been investigated for local traverse.
- In the small body exploration case we have studied a collaborative Visual SLAM algorithm between the orbiter and the deployed daughter.

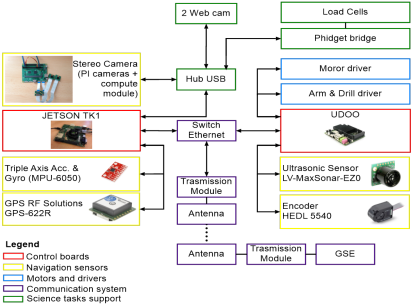
Field Robotics Testbed



Mechanical configuration

Stereo Visual SLAM Test

- Planetary like rover designed by a team of students
- Testbed for soil and rocks extraction and sampling
- Testbed for autonomous navigation in unstructured environment (sensors and algorithms)



Rover Sensors

Pubblications

UNIVERSITÀ DEGLI STUDI DI PADOVA

- **Chiodini, S.**, Colombatti, G., Pertile, M., Debei, S. Numerical study of lander effects on DREAMS scientific package measurements (2014) 2014 IEEE International Workshop on Metrology for Aerospace, MetroAeroSpace 2014 - Proceedings, pp. 433-438.
- Pertile, M., **Chiodini, S.**, Debei, S. Comparison of visual odometry systems suitable for planetary exploration (2014) 2014 IEEE International Workshop on Metrology for Aerospace, MetroAeroSpace 2014 - Proceedings, pp. 232-237.
- Colombatti, G., **Chiodini, S.**, Friso, E., Aboudan, A., Bettanini, C., Debei, S., Esposito, F. MarsTEM: The temperature sensor of the DREAMS package onboard ExoMars 2016 (2014) 2014 IEEE International Workshop on Metrology for Aerospace, MetroAeroSpace 2014 - Proceedings, pp. 249-254.
- Pertile M., Mazzucato M., Bottaro L., ,**Chiodini S.**, Debei S. and Lorenzini E. Uncertainty evaluation of a vision system for pose measurement of a spacecraft with fiducial markers (2015) 2nd IEEE International Workshop on Metrology for Aerospace, MetroAeroSpace 2015 - Proceedings, pp. 283-288.
- Colombatti G., **Chiodini S.**, Friso E., Aboudan A., Bettanini C., Poli M., Debei S., Esposito F., Molfese C., Schipani P., Marty L., Mugnuolo R., Pirrotta S. and Marchetti E. MarsTEM field test in Mars analog environment (2015) 2nd IEEE International Workshop on Metrology for Aerospace, MetroAeroSpace 2015 - Proceedings, pp. 585-590.
- **Chiodini S.**, Colombatti G., Friso E., Pertile M. and Debei, S. Multiphysics modelling of MarsTEM shield (2015), 2nd IEEE International Workshop on Metrology for Aerospace, MetroAeroSpace 2015 - Proceedings 271-276.
- Pertile M., **Chiodini S.**, Debei S. and Lorenzini E. Uncertainty comparison of three visual odometry systems in different operative conditions (January 2016), Measurement 78.
- **Chiodini S.**, Pertile M. and Debei S. Visual odometry system performance for different landmark average distances IEEE Metrology for Aerospace (MetroAeroSpace), 2016.
- Pertile M., **Chiodini S.**, Giubilato R. and Debei S. (2016, June). Effect of rolling shutter on visual odometry systems suitable for planetary exploration. In Metrology for Aerospace (MetroAeroSpace), 2016 IEEE (pp. 598-603).