Application of Simultaneous Localization and Mapping algorithm to Terrain Relative Navigation for Lunar Landing

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Contents:

Introduction to INVERITAS

Innovative Technologie zur Relativnavigation und Capture mobiler autonomer Systeme

- R&T project supported by the Agency of the German Aerospace Center (DLR) funded by the Federal Ministry of Economy and Technology, reference number 50RA0908
- Objective to develop and enhance the Technology Readiness Level (TRL) of a series of Technologies for Relative Navigation near non-cooperative targets or unknown surfaces
- Analysis of the application of technologies to Lunar and Mars Exploration scenarios

Typical Mission Profile for Lunar Landing Mission

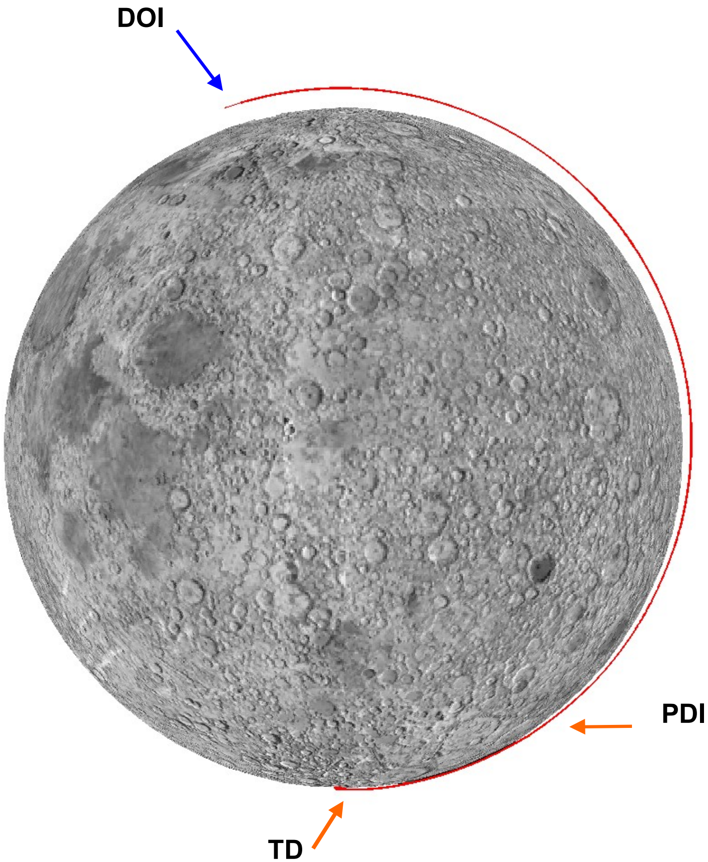


Fig. 1 Example of Typical Mission Profile for Lunar Landing from Low Lunar Orbit to descent, braking and final landing.

1. Interplanetary Travel to the Moon
2. Low Lunar Orbit
3. Descent Orbit (Ballistic Flight)
4. Braking Phase
5. Retargeting
6. Final Descent and Landing

Start of Braking	h=10 km	V=1.6 km/s
End of Braking	h=1.5 km	V=0.1 km/s

DOI: Descent Orbit Initiation

PDI: Powered Descent Initiation

TD: Touch Down

Definition of Precise and Safe Landing on the Moon

Requirements for Apollo/Surveyor Missions at touchdown (NASA 1966) [JSC-37000]:

- **Max Error Position: ~3.2 km**
- **Velocity: <2.1 m/s (vertical), <1.2 m/s (horizontal)**
- **Attitude: <3 deg**
- **Rotation Rate: <3 deg/sec**

Requirements for NEXT Lunar Lander at touchdown:

- **Max Error Position: 200 m 3σ (in planet frame), 9 m 3σ (w.r.t. to last target) (Precision Landing)**
- **Velocity: <(1.5* m/s + 1m/s 3σ) (vertical), <1 m/s 3σ (horizontal) (Safe Landing)**
- **Attitude: 2 deg 3σ (Safe Landing)**
- **Rotation Rate: 2.5 deg/sec 3σ (Safe Landing)**

Navigation Estimation Errors must be significantly smaller in order to allow to reach these conditions

[*] Nominal value of vertical velocity at touchdown

Definitions of Absolute and Relative Visual Navigation Systems

Absolute Visual Navigation (AVNAV)

- **Autonomous system able to recognize current position and attitude with respect to the terrain**
- On-board sensor: optical camera (no range constraints)
- Performance strongly depending on the availability and quality of surface information (i.e. DEM, Maps, Images).
- Provides **good initialization for navigation at lower altitudes** where no data is available

Relative Visual Navigation (RVNAV)

- Tracking of ground features through time can provide **information about velocity and rotation between frames** even though leaving the biases in position estimation unchanged
- Several concepts have been developed which include different sensors and algorithms mostly relying on **Range Information (i.e. LIDAR, RADAR, Stereocameras…)** and **Visual Information (i.e. Cameras)**
- Generally RVNAV is assumed to be **provided with a good initialization by AVNAV** and aims to **slow down increase of estimation errors**
- Alternatively RVNAV techniques can provide a **model for target relative navigation**

This work involves the development of a reliable relative navigation system and assessment of its performance in landing site proximity (i.e. end of braking)

Implemented Relative Visual Navigation Concept based on SLAM algorithm

Scenario: End of braking, state information provided from AVNAV

Challenge: Navigate in an unknown environment

Goals:

1. Provide accurate velocity information to avoid error divergence

2. Achieve precision landing at new targeted Landing Site

- **S**imultaneous **L**ocalization **A**nd **M**apping (SLAM) algorithm
- Standard Extended Kalman Filter (EKF) SLAM implementation
- Inspired to the NPAL experience [NPAL-06]

Builds up a stochastic map (i.e. estimates position of tracked features)

Estimates spacecraft velocity with respect to the map

Does not provide correction for initial position error

Needs a good initialization

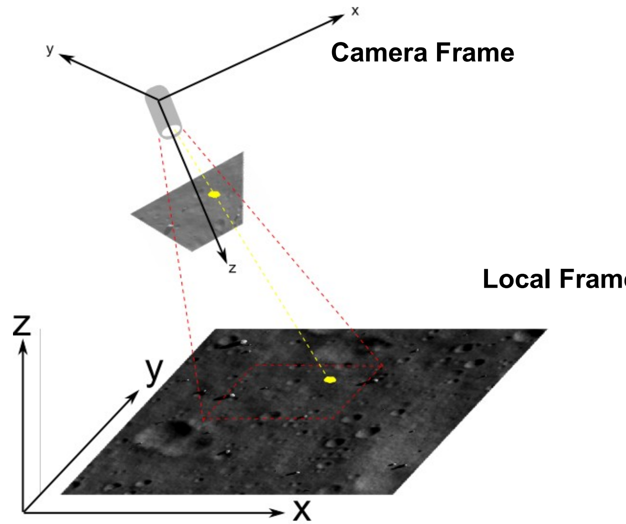


Fig. 2 Feature Points in Camera and Local Frame (LS centered)

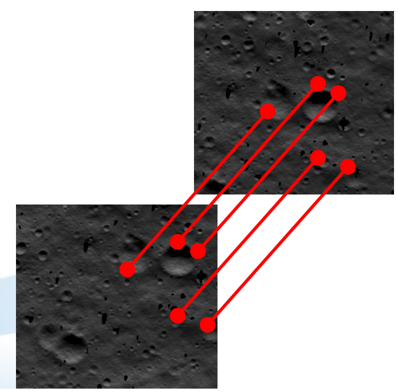


Fig. 3 Example of Features Tracking between consecutive images

Implemented Relative Visual Navigation Concept based on SLAM algorithm (2)

- **Estimation Process:**
  - **Features are extracted from camera image and tracked**
  - **Such bearing-only measurements are fed within the Extended Kalman Filter (EKF)**
  - **Range to surface is provided by a RADAR altimeter**
  - **Features 3D position components are initiated on zero altitude plane**
  - **The state vector of the spacecraft is added of the estimated features positions**
  - **The EKF fuses such measurements with IMU data in order to provide optimal state estimation**

- **Sensors:**
  - **IMU: realistic values for noise, biases and scale factors (ref. Honeywell MIMU and QFLEX accelerometer with bias compensated until 25µg)**
  - **Radar altimeter: realistic values for noise, biases and scale factors (ref. Honeywell HG8500)**
  - **Camera: 512x512 pixels, FoV 70 deg, 10Hz sampling**

Features Detector: Shi -Tomasi

Features Tracker: Lukas - Kanade

Propagation Rate: 10Hz

Update Rate: 10Hz

•Standard Algorithms from the robotics community

•Flight validated hardware

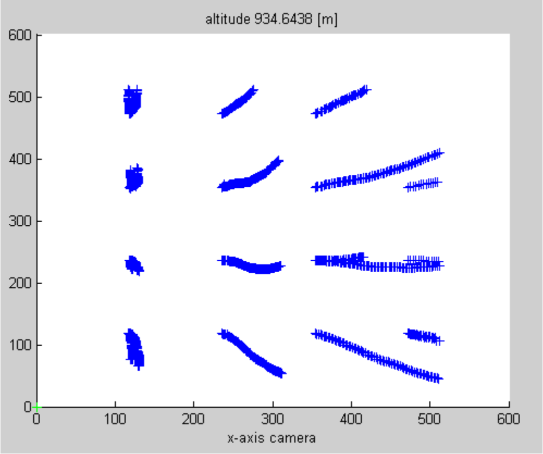
•Navigation in landing site proximity

Image Source, Quality and Processing

- Perfect camera model

1. Homogeneus distributions of points in FoV
2. Perfectly flat surface of the Planet
3. Continuous tracking of features

Fig. 4 Visual Flow for perfect camera



- Images from Pangu 2.7 for different camera poses with image processing

- Accuracy limited by map resolution
- Possible blinking features
- Possible overlapping of features
- Complicated shape of terrain
- Dependency on lightening conditions

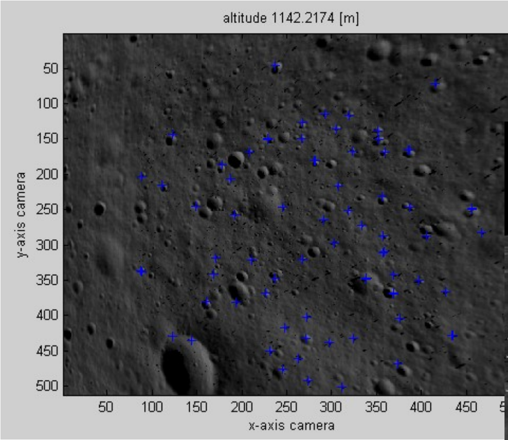


Fig. 5 Tracked Features for Pangu Camera

Fig. 6 Typical Pangu Scenario

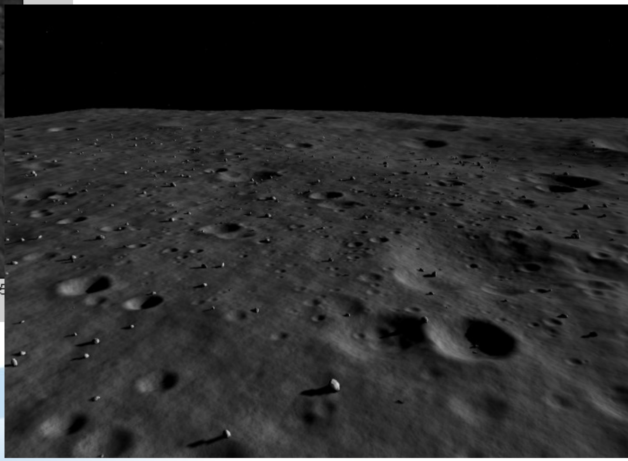


Image Source, Quality and Processing (2)

- Relevant criteria for performance of the filter

1. **Spatial distribution of points** (maximize the entropy of distribution of feature points) in the field of view
2. **Performance of features tracking** (no sliding feature positions)
3. **Repeatability between consecutive frames** (no blinking features)

- Need for Image Processing

1. A large number of points have to be tracked and according to their characteristics (i.e. distribution, repeatability) are fed into the filter
2. Features which are in the proximity of a tracked feature have to be discarded in order to improve distribution and increase information provided by the optical flow

GNC Architecture

- All Simulations in Closed Loop
- Retargeting Capability
  - **Target Estimation error correlated spacecraft state estimation error**
  - **Baseline of two retargetings**
- Real Time Trajectory Generation (E-Guidance, reconfigurable)
  - **Generation of new trajectory from current state estimates to new Landing Site**
- Thrust Vector Control (LQR controller)
- Clustered Engines concept:
  - **RCS: 16 ACS (22N each)**
  - **Main Engines: 5 EAMs (500N each), 6 ATV (220 N each)**

Performance of a Relative Visual Navigation Systems in closed loop

- **Closed Loop Simulations**
- **Single Trial, Final Landing (i.e. last 700 meters along track, 1500 meters altitude)**
- **1% dispersion in nominal values of velocity (~1.4m/s) and attitude**
- **No error in initial horizontal position (altitude error driven by Altimeter)**
- **Targeting to initial nominal Landing Site**
- **Perfect Camera Model**

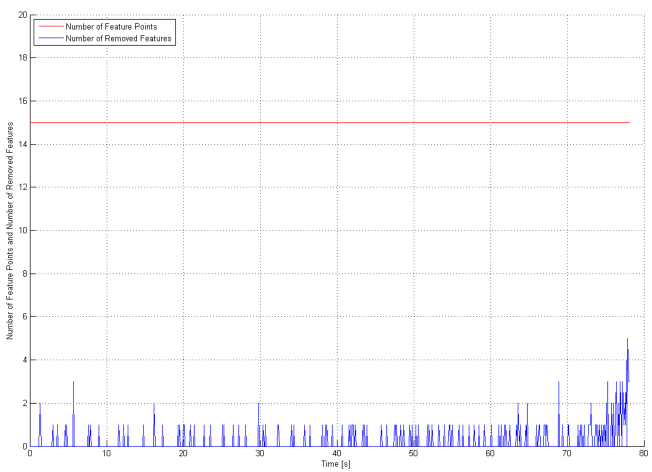


Fig. 7 Example of Feature Points Management: Total (red) and removed (blue) feature points per step

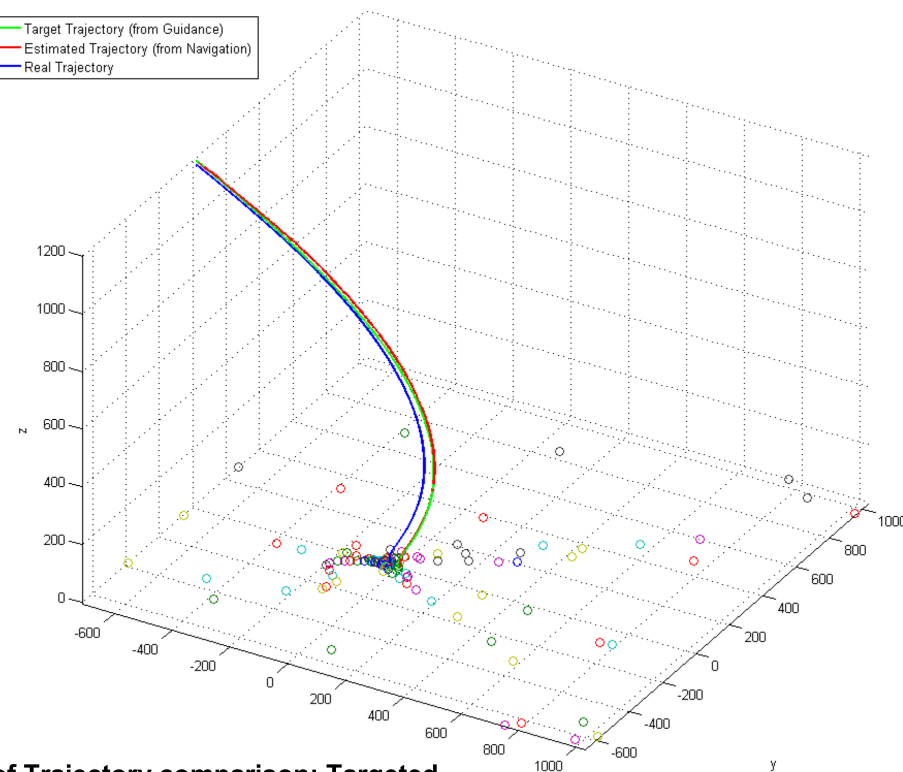


Fig. 8 Example of Trajectory comparison: Targeted, Real and Estimated Trajectory with simulated feature points lying on a zero altitude plane

Performance of a Relative Visual Navigation Systems in closed loop (2)

Closed Loop Simulations for IMU-Altimeter Navigation and for SLAM Algorithm

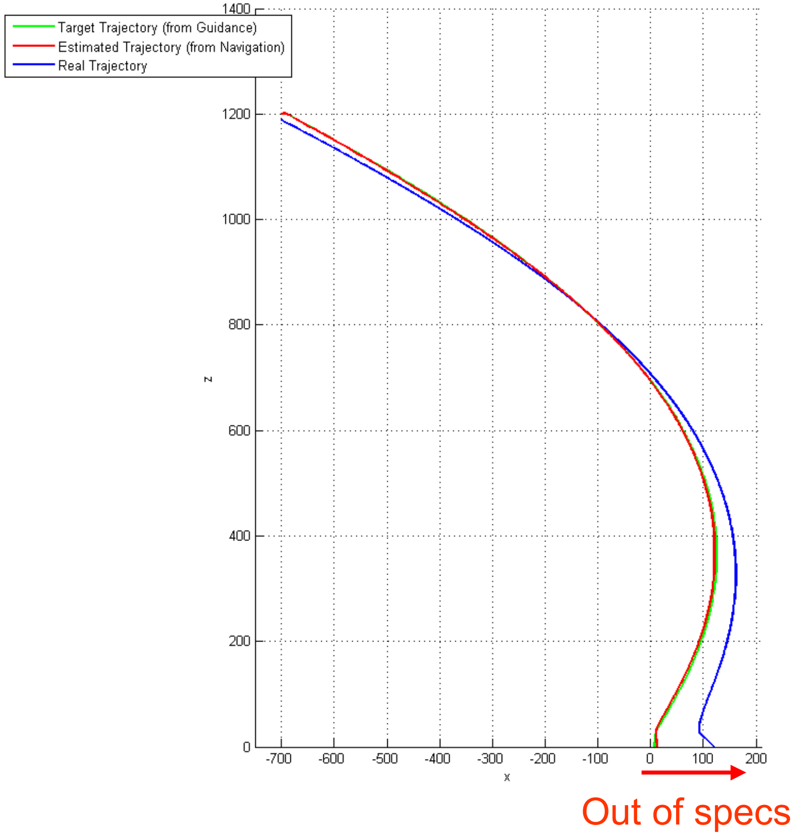


Fig. 9 Trajectories Comparison for IMU-Radar Navigation Chain

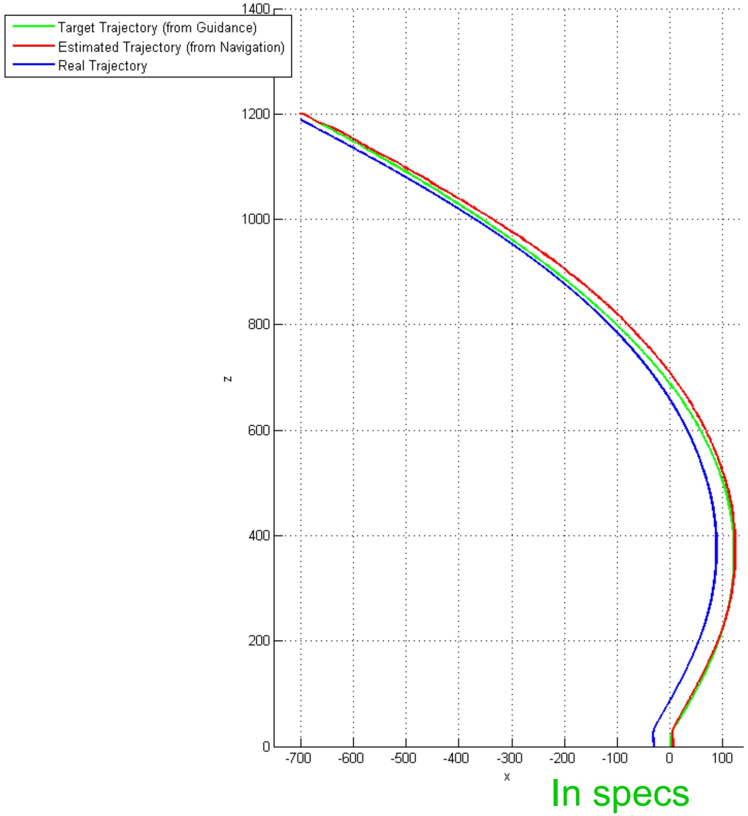


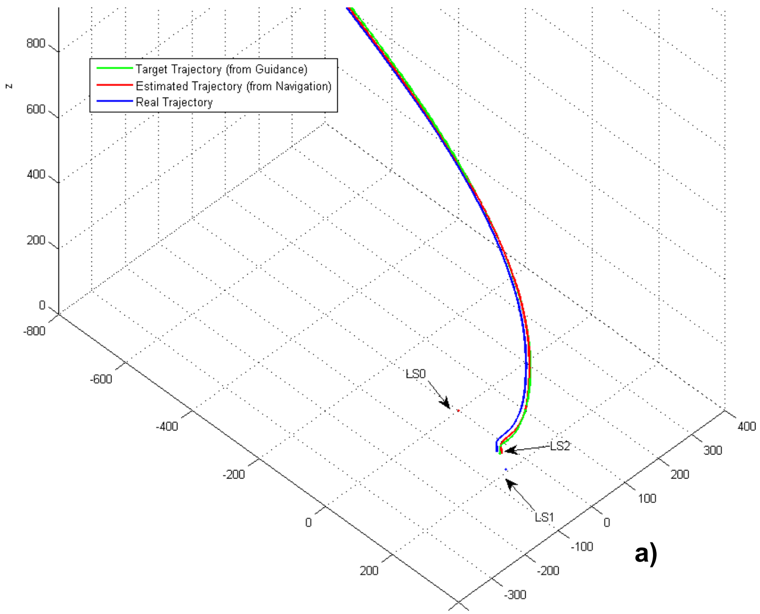
Fig. 10 Trajectories Comparison for Relative Visual Navigation with Perfect Camera Model

Performance of a Relative Visual Navigation Systems in closed loop (3)

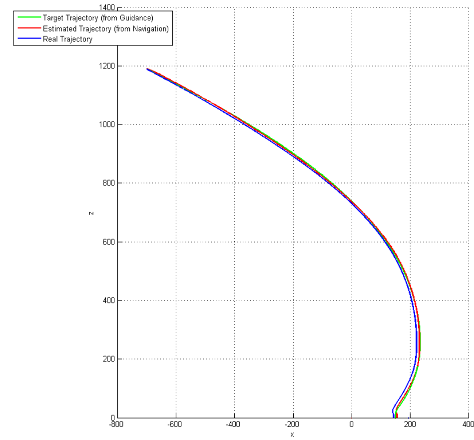
- Closed Loop Simulations with PANGU imager
- Single Trial, Final Landing (i.e. last 700 meters along track , 1500 meters altitude)
- No error in initial horizontal position (altitude error driven by Altimeter)
- Very high velocity estimation errors of 1m/s in the three directions
- Two Retargetings of respectively 200 m and 50 m
- 100 features are tracked, 15 features are added to the filter state and processed
- Last 20 meters with IMU-Altimeter Navigation only

Objective: challenge the navigation system in a closed loop, multiple retargetings scenario and provide an assessment of the overall GNC robustness

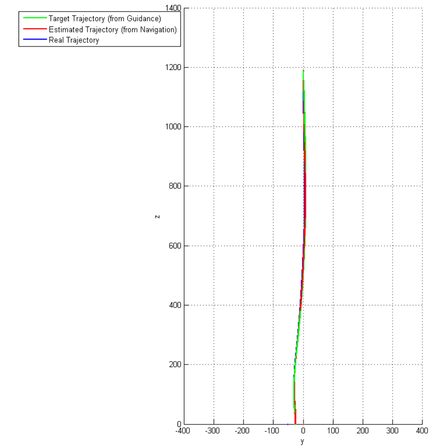
Performance of a Relative Visual Navigation Systems in closed loop (4)



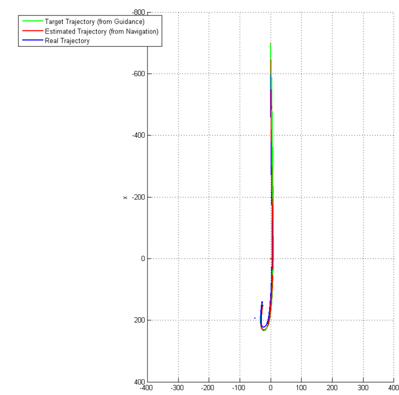
a)



b)



c)



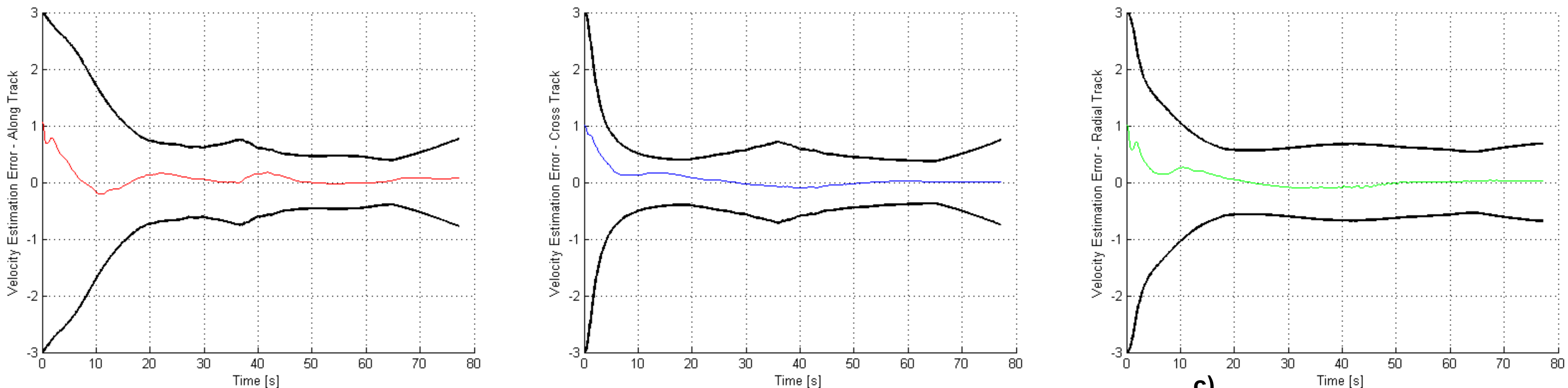
d)

Miss Distance:	**<6.7 m**	**(~4.2 m due to Control dispersions)**
Speed:	**<0.1m/s (Horizontal)**	**-1.5 m/s + 0.03 (Vertical)**
Angles:	**[0.0, 0.4, 0.2] deg**	
Rates:	**[0.2, -0.1, 0.0] deg/s**	

Performance within the Specs

Fig. 11 Trajectories comparison for two retargetings scenario a) 3D trajectory and Landing sites b) x-z plane c)y-z plane d)x-y plane

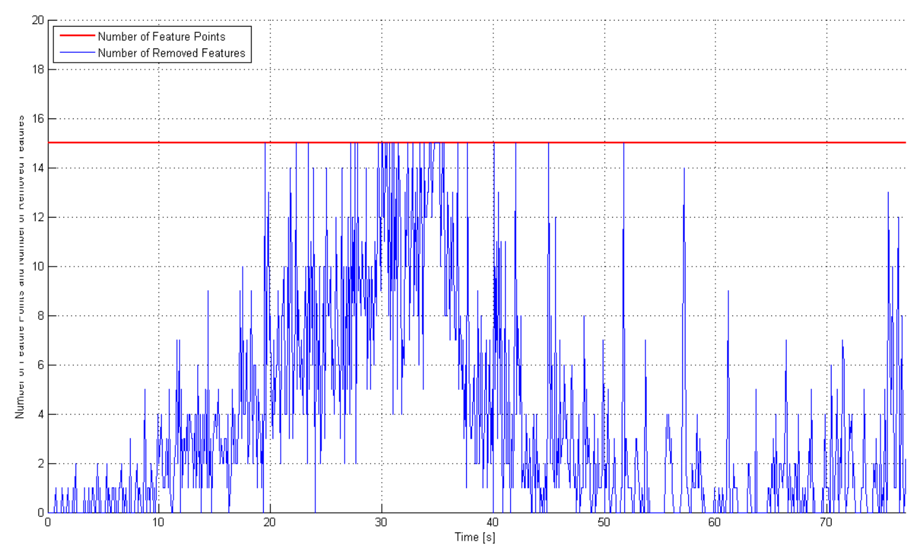
Performance of a Relative Visual Navigation Systems in closed loop (4)



a) b) c)

Fig. 12 Velocity Estimation Error a) Along Track, b) Cross Track, c) Radial Track

Fig. 13 Total features in the Filter (red), Removed Features (blu)



Good Performance in Velocity Estimation

Error Velocity at TD: [0.075 0.015 0.025] m/s

Navigation Robust to re-initialization of tracked features

Improvement expected with better imagery

Performance of a Relative Visual Navigation Systems in closed loop (5)

- Images from Pangu
- Rapid change of feature points
- Necessary control over the tracked/removed ratio
- Undulating, not flat, Terrain
- Overlapping Features
- No homogeneous distributions of features
- Mapping Resolution limitations

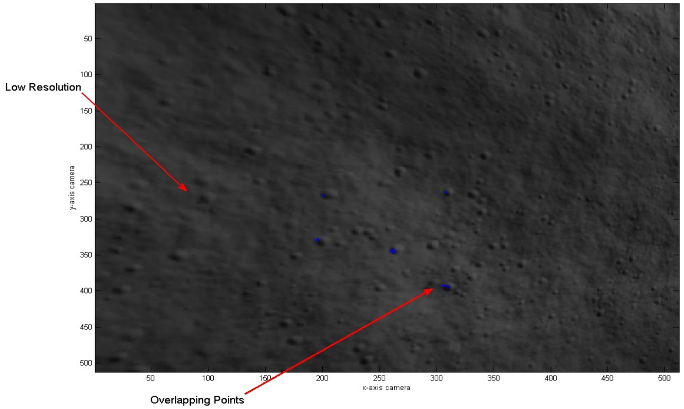
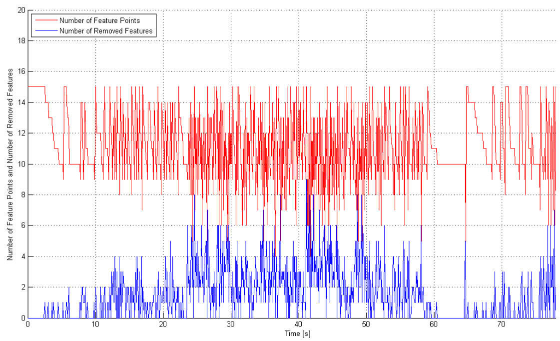
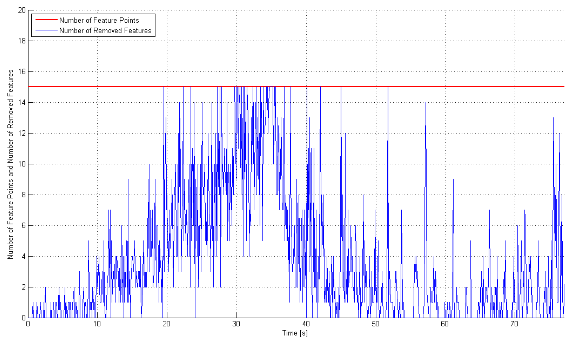


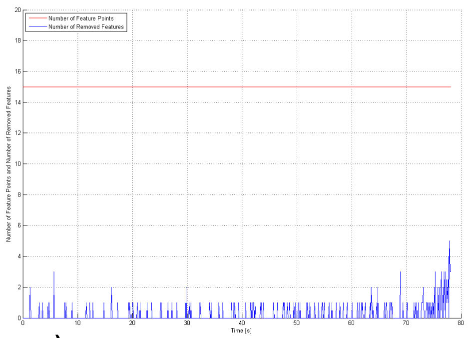
Fig. 14 Example of Pangu Image while approaching the ground: resolution becomes poor while feature points tend to overlap



a)



b)



c)

Fig. 15 Typical behavior of tracked Features number with Pangu Camera a) without feature control, b) with feature control and c) for perfect Camera. Total (red) and removed (blue) feature points per step

Conclusions and Future Work

- A SLAM algorithm has been developed and implemented as main navigation algorithm within the last phase of a lunar landing scenario making use of well established algorithms from the robotics community
- It provides good velocity estimation
- Closed-Loop Validation proves accuracy in achieving targeted Landing Site

Future work will encompass:

- Improve image processing (more homogeneous distributions of features in the FoV, robustness to lightning conditions and scale transitions)
- Extend the visual navigation to the powered descend (e.g. from 8 km altitude)
- Improve initialization of the features
- Improve tuning of control system
- Test with realistic imagery of moon surface
- Long term goal: develop a fully autonomous Target-Relative Navigation for unknown environments

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