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VISION-BASED ALGORITHMS AND ROBUST FILTERING FOR STATE ESTIMATION OF AN UNCOOPERATIVE OBJECT IN SPACE

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Outline

- Autonomous spacecraft proximity operations
- System Architecture
- Vision Based tracking
- Filtering Techniques
- Simulations
- Conclusions
- Future developments

Autonomous spacecraft proximity operations

PoliMi-DAER is developing dedicated algorithms for vision based autonomous spacecraft proximity operations:

Target type	Relative navigation hardware (Chaser)	Relative navigation hardware (Target)	Possible mission scenario
Actively cooperative	RF transmitting/receiving antennas	RF transmitting/receiving antennas	FF,OOS
	GNSS module, communication antenna	GNSS module, communication antenna	
Passively cooperative	Active/passive sensors	LEDs, CCRs	FF, OOS
Uncooperative known	Active/passive sensors	N/A	**FF, OOS, ADR**
Uncooperative unknown	Active/passive sensors	N/A	ADR, comet/asteroid exploration

Autonomous spacecraft proximity operations

***Passive vs. active* Sensors** → Cameras are selected

Advantages

- Lower hardware complexity, cost and power consumption

Drawbacks

- More sensitive to variation in illumination and target reflectivity conditions, background noise

Monocular vs. stereo → Monocular systems are preferred

→ **Visual Odometry like routine with frame to 3D-Model matching**

Filtering vs. non filtering → Filtering is selected

Advantages

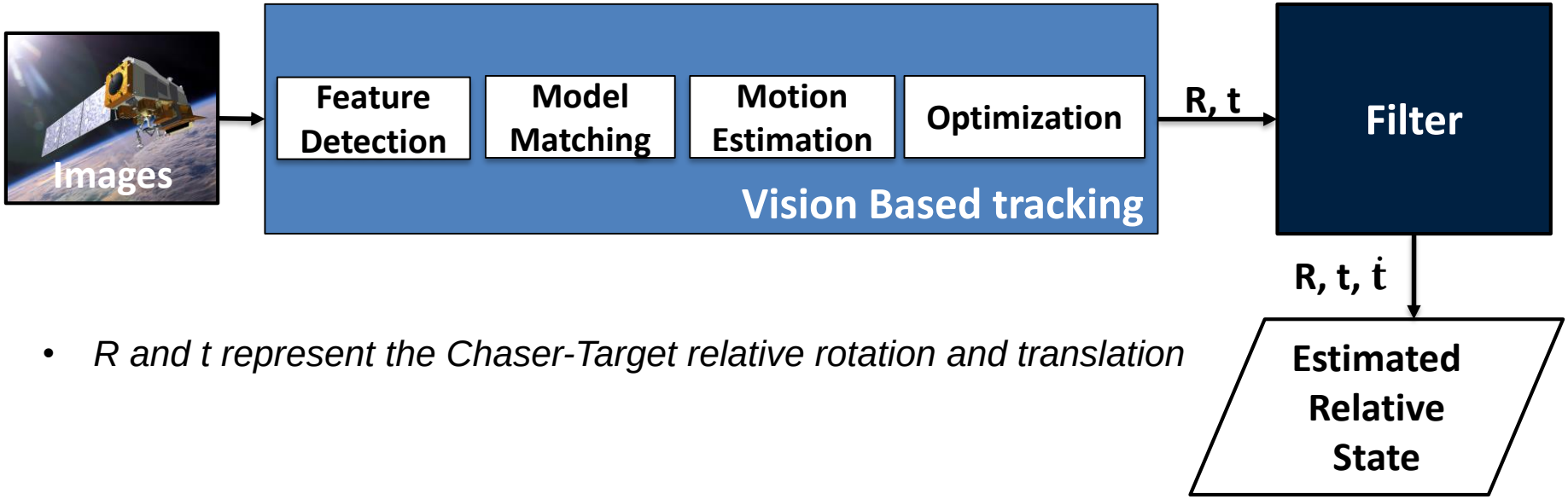
- Accuracy, velocities estimation, robustness against erroneous tracked motions

Drawbacks

- Higher computational burden and complexity of the system

→ **Robust filtering with separated motion and rotations**

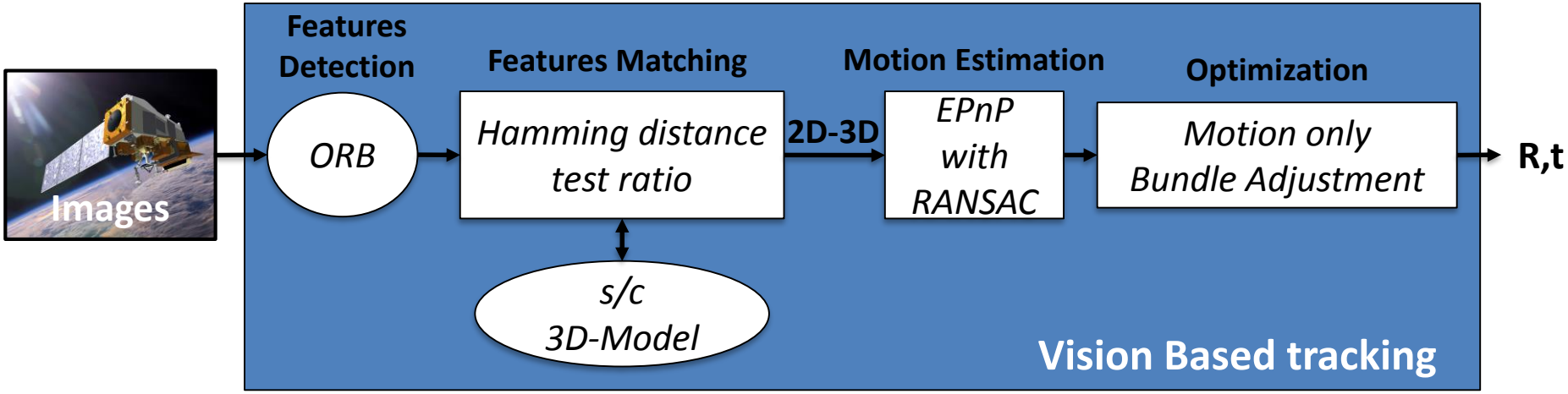
System Architecture



- *R and t represent the Chaser-Target relative rotation and translation*

➢ Incoming images from the monocamera are first processed by the **Vision Based tracking**, which gives a first estimation of the Chaser-Target relative postion and orientation (pose), which is then used as first guess by the **filter** for the complete relative state estimation.

Vision Based tracking



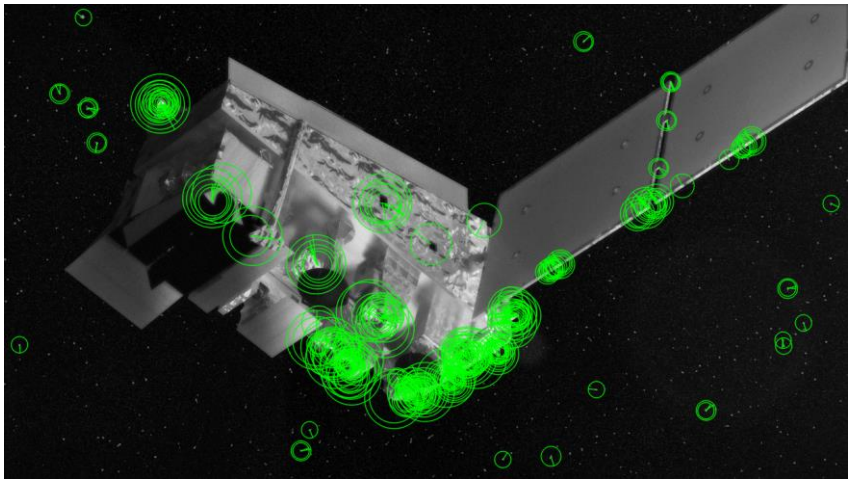
Single grayscale images from the monocamera are processed:

- **Features detection**, salient features are extracted from the image with correspondent descriptors.
- **Matching**, detected features are matched to an on-board Target spacecraft **3D-model** correlated with descriptors.
- **Relative pose** is estimated solving the **P*n*P problem** given the 2D to 3D set of correspondences previously built.
- **Motion only Bundle Adjustment** is run after each motion estimation step to optimize the retrieved pose reducing the *reprojection error*.

Vision Based Tracking - Features detection & matching

ORB detector is exploited for features extraction:

- Fast to compute.
- Invariance to viewpoint.
- Scale invariant.
- Robust to light changes.
- 300 features extracted to keep low computational burden.



Hamming distance test ratio used to robustly match extracted features with on-board target satellite *3D-model*

- *Hamming distance*: $\mathrm{e.g.}\ dH(D1, D2) = dH(10\mathbf{1}1\mathbf{1}01, 10\mathbf{0}1\mathbf{0}01) = 2$
  (D1,D2 descriptors)
- *Test ratio: if* $\frac{dH_{11}}{dH_{12}} < 0.7 \div 0.8$ *then* <u>*Good Match*</u>
  (dH_{11}, dH_{12} first and second minor distance)

3D-Model of the target is built on ground exploiting CAD models and multiple images to obtain a set of 3D sparse points with correlated descriptors.

Vision Based tracking - Motion estimation & optimization

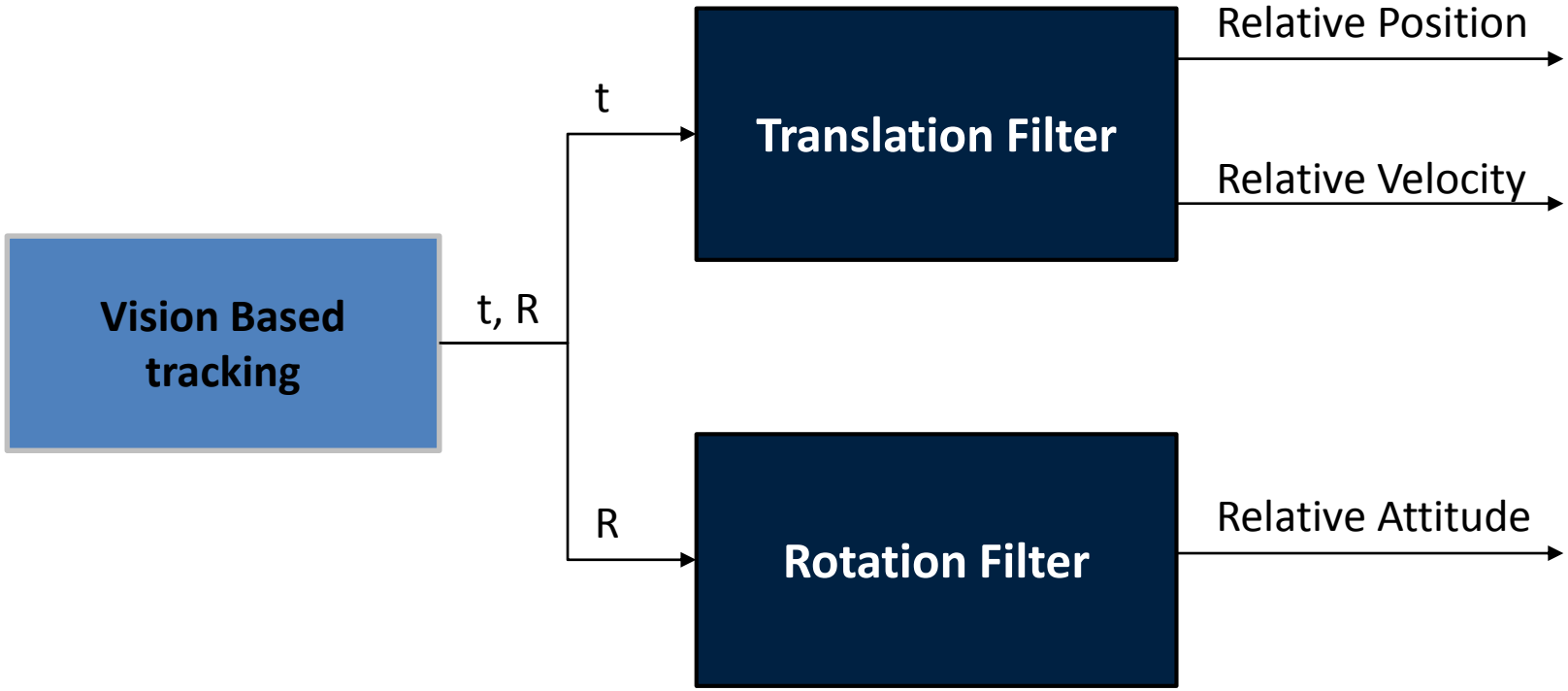
Relative pose of the Target is retrieved with **EPnP algorithm**

- Non-iterative efficient solution to the P*n*P problem.
- Applicable for both planar and non planar 3D point cloud configurations.
- Implemented within a RANSAC routine to be robust to the presence of outliers.

Motion only Bundle Adjustment is implemented as a hyper graph

- Fast non-linear least squares optimization techinique adopted in *Computer Vision*.
- Only relative pose is optimized, 3D map is kept fixed.
- 2D features represent the *measurements* connecting the 3D points and the relative pose that instead are the *vertices* of the hyper graph.

Filtering Techniques



Filtering Techniques - Translation

- Dynamical Model: Yamanaka and Ankersen linearized state transition matrix for arbitrary elliptical orbits.[1]

- Measurements: relative position available from the Pose Determination block

- H∞ Filter robust filtering technique. It minimizes the worst case estimation error.

$$P_{K+1} = F_k P_k [I - \theta P_k + {H_k}^T {R_k}^{-1} H_k P_k]^{-1} F^T + Q_k$$

$$K_k = P_k [I - \theta P_k + {H_k}^T {R_k}^{-1} H_k P_k]^{-1} {H_k}^T {R_k}^{-1}$$

1. K. Yamanaka and F. Ankersen, "New state transition matrix for relative motion on an arbitrary elliptical orbit," Journal of guidance, control, and dynamics, vol. 25, no. 1, pp. 60–66, 2002.

Filtering Techniques - Rotation

- Second Order Filter on the SO(3) group developed by Zamani et al.[2] for absolute attitude estimation.
- Measurements: relative rotation matrix available from the Pose Determination block – no relative angular velocity measurements.

$$\dot{R} = R(\omega(t)_\times)$$
$$\dot{\omega} = 0 + B\delta$$

$$\dot{\hat{R}} = \hat{R}\left(\hat{\omega}(t) + K_{11}r^R + K_{12}r^\omega\right)_\times ,$$
$$\dot{\hat{\omega}} = K_{21}r^R + K_{22}r^\omega,$$
$$\dot{K}(t) = -\alpha K + AK + KA^T - KEK + GQ^{-1}G^T - WK - KW^T$$

2. M. Zamani, J. Trumpf, and R. Mahony, "Minimum-energy filtering for attitude estimation," IEEE Transactions on Automatic Control, vol. 58, no. 11, pp. 2917–2921, 2013.

Simulations

First simulations have been run on **synthetic image sequences** generated from scratch:

- General satellite 3D model considered.
- Relative trajectory imposed.
- Features generated directly projecting 3D-model on image plane.

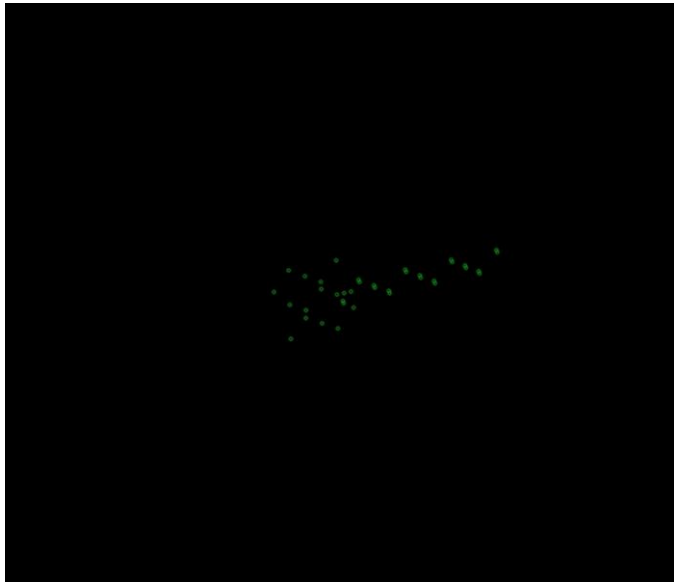
Noise is introduced in different ways to simulate as close as possible a real scenario:

- Non perfect absolute state determination of the chaser spacecraft.
- Uncertainty in 2D features location.
- Errors in the target spacecraft 3D model.

➢ Two simulation scenario are considered.

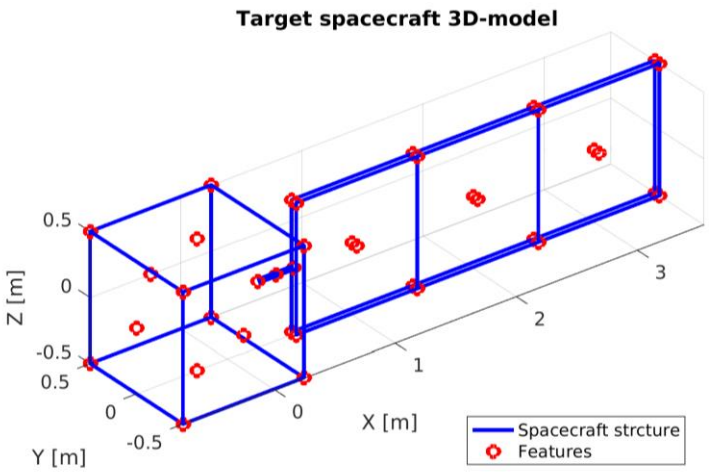
Simulations – Scenario A

- MEO orbit with *e=0.17*
- Relative initial position $\rho_0 = [50, 0, 0]\ m$
- Relative initial velocity
  $\dot{\rho}_0 = [0, -0.1, 0]\,\frac{m}{s}$
- Relative initial angular velocity
  $\omega_0 = [1, 0.1, 0.3]\,\frac{deg}{s}$
- Frequency: *10Hz*

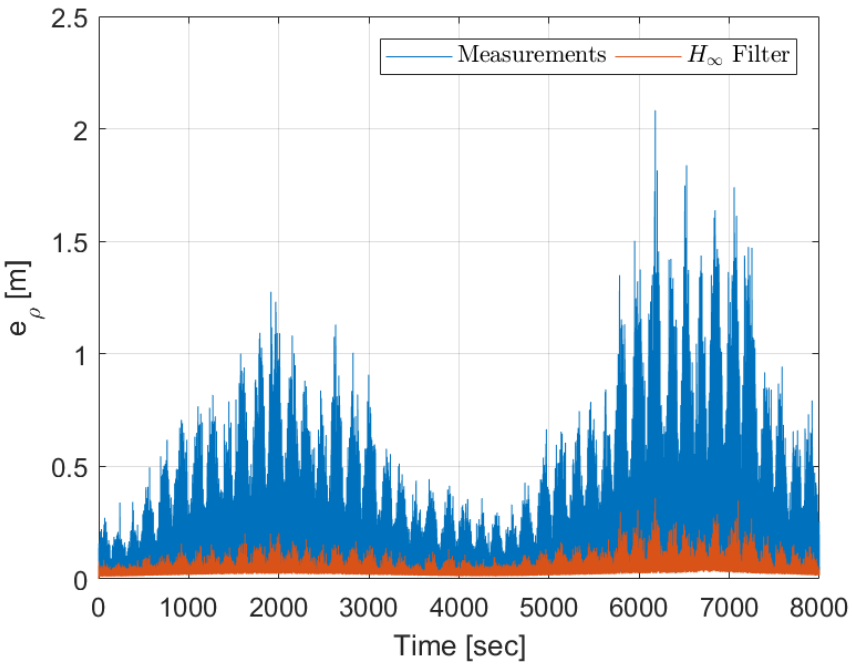


- Absolute state error:
  - Position $\sigma = 10^{-2} km$
  - Velocity $\sigma = 10^{-4}\,\frac{km}{s}$

- NPP Satellite Model
- Feature Points Extraction Noise
  $\sigma_{pix} = 2$

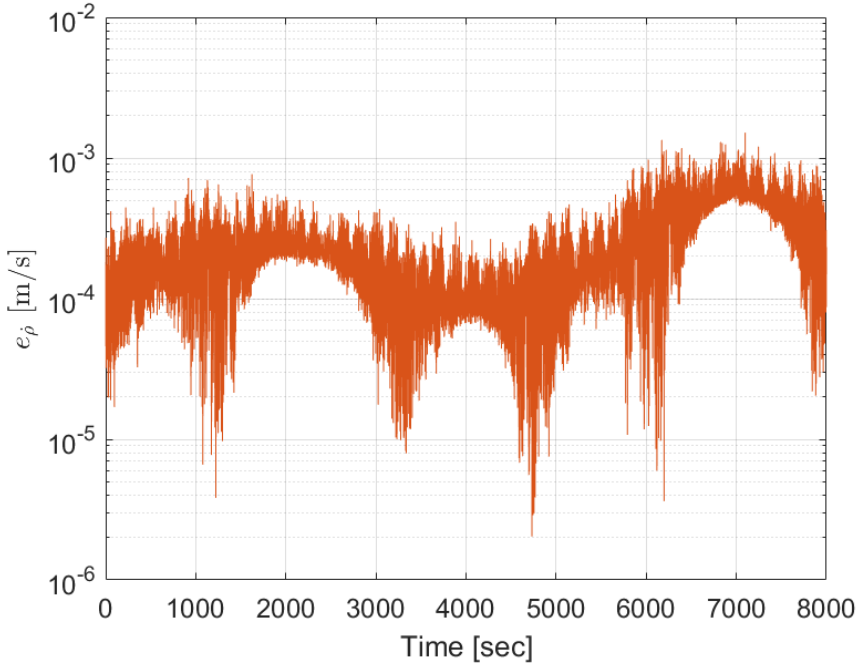


Simulations - Translational results



Relative Position Error

$$e_\rho = \sqrt{(x_i - \hat{x}_i)^2 + (y_i - \hat{y}_i)^2 + (z_i - \hat{z}_i)^2}$$

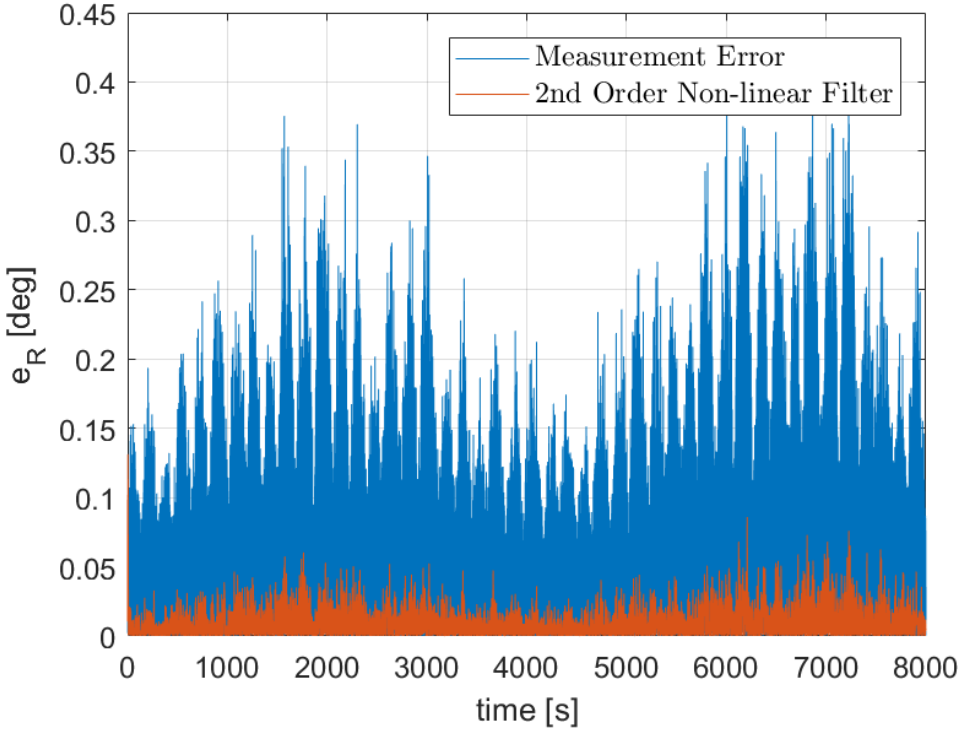


Relative Velocity Error

$$e_{\dot{\rho}} = \sqrt{(\dot{x}_i - \hat{\dot{x}}_i)^2 + (\dot{y}_i - \hat{\dot{y}}_i)^2 + (\dot{z}_i - \hat{\dot{z}}_i)^2}$$

- Estimated position error with Vision Based tracking routine is always below *2 m.*
- Filtering improves accuracy reducing error below *0.3 m.*
- Velocities are estimated with high accuracy.

Simulations - Rotational results



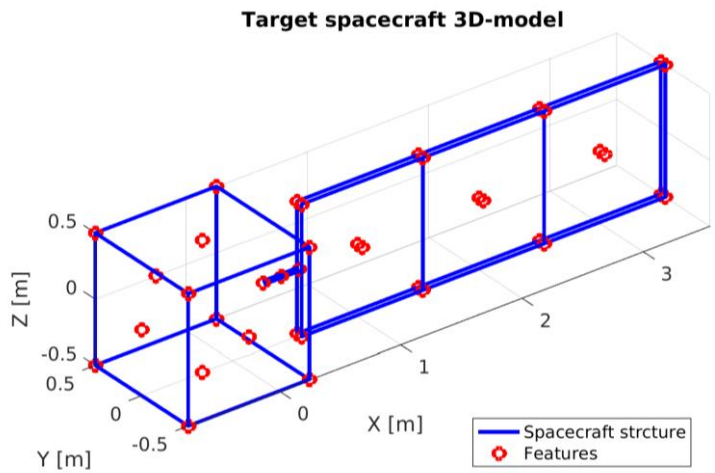
Relative Rotation Error

$$e_R = acos\left(1 - \frac{tr(I - R_i{}^T \hat{R}_i)}{2}\right)$$

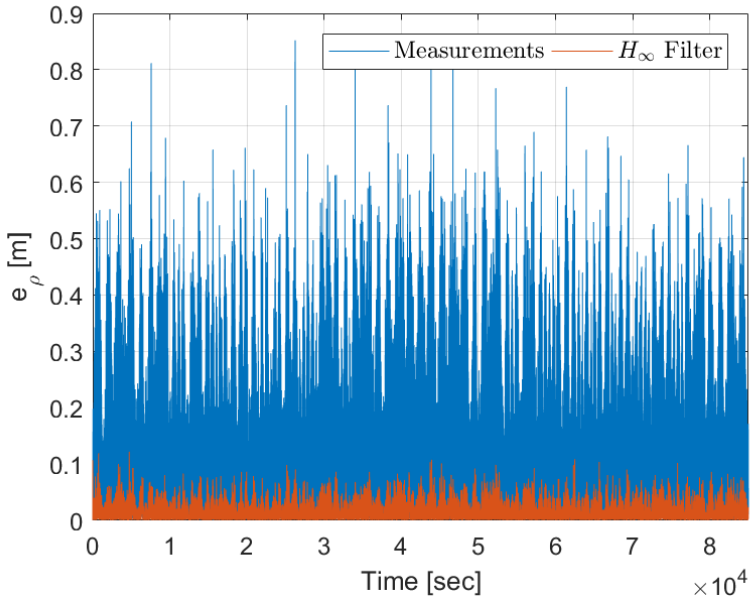
- Rotations are retrieved with errors around 0.4° by the Vision Based tracking.
- Rotation filter improves the estimation reducing error down to 0.05 °

Simulations – Scenario B

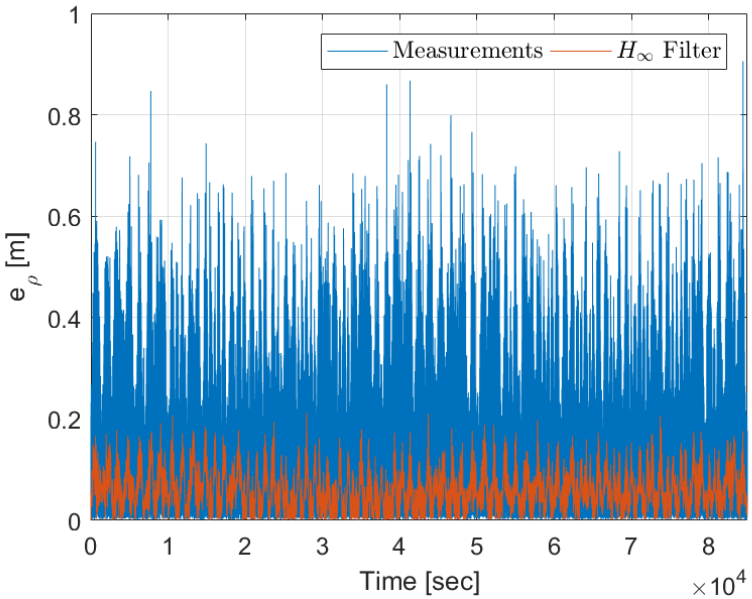
- **GEO orbit**
- Relative initial position $\rho_0 = [0, 50, 0]\ m$
- Relative initial angular velocity $\omega_0 = [\mathbf{0.07}, 0.1, 0.3]\ \frac{deg}{s}$
- **Frequency:** ***1Hz***
- **Additional Error to the target spacecraft 3D-Model added.**



Simulations - Translational results



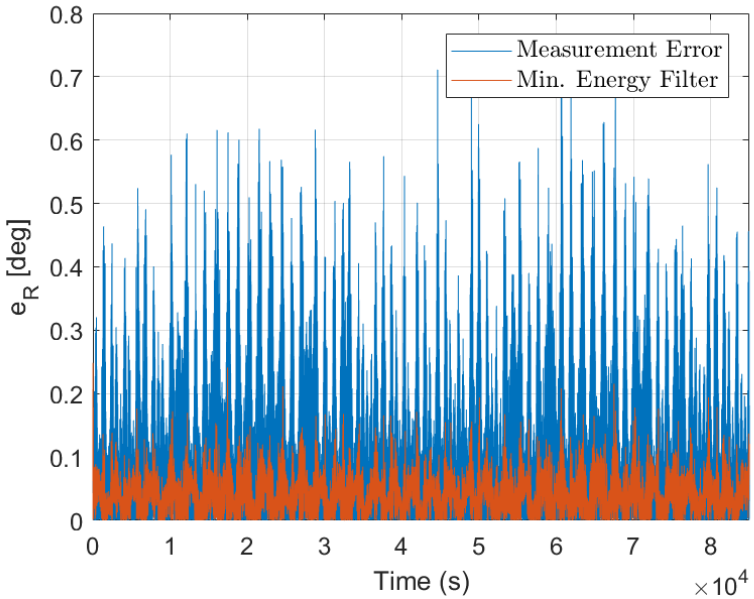
Relative Position Error
without Noise on the Map



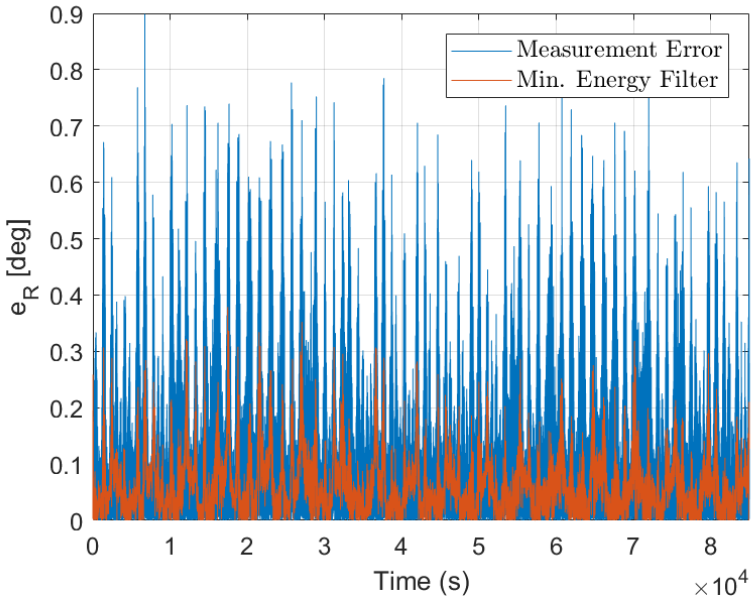
Relative Position Error
with Noise on the Map

- The overall error is small in both cases.
- The estimation error of the relative position increases with the noise on the map. This is due to the resulting pixels and map combinated noise.
- The lower frequency does not affect the estimates.

Simulations - Rotational results



Relative Rotation Error without Noise on the Map



Relative Rotation Error with Noise on the Map

- The estimation error of the relative rotation increases with the added noise on the map. This is due to the resulting pixels and map combinated noise.
- Rotations are still retrieved with good accuracy even with the introduced map error.

Conclusions

A Vision-Based algorithm with robust filtering for state estimation of uncooperative objects is under development at PoliMi – DAER:

- Fast and accurate Vision Based tracking algorithm for spacecraft relative pose determination.
- Clear benefit of using a filter for translational & rotational dynamics.
- Tests campaign on simulated scenarios performed.
- The overall preliminary performance of the algorithm are satisfactory.

Future developments

- Extensive analysis with different simulations scenarios.
- Heavy development of a routine for the Target spacecraft 3D-Model on ground construction.
- Test the Vision-Based tracking algorithm with synthetic and real images.
- Experimental validation on test facility currently under setup at PoliMi DAER.

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