A Small Platform Application for Close Inspection of an Uncontrolled Satellite

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Space Proximity Operations: the framework

- Small servicing platforms are becoming of greater interest for on-orbit missions
- Visual inspection, Active Debris Removal and satellite maintenance represent the main space proximity operations
- High level of operational autonomy is required as the target is usually non-cooperative and uncontrolled due to possible failures

Mission Scenario

Small platform application for close visual inspection of an out-of-control, freely tumbling satellite

- **Close visual inspection** of the target is useful for an estimate of potential external damages and failures (solar panels, loss of propellant, antennas, etc.)

- Close visual evaluation is carried out by means of an **inspecting camera** mounted on a robotic arm, operated only at a close range

- **Distance sensor** and **navigation camera** used to meet mission requirements

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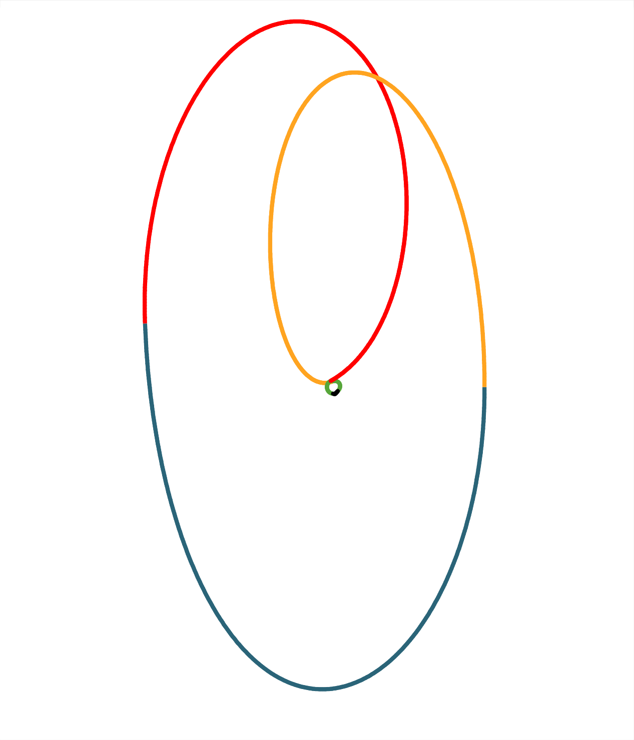
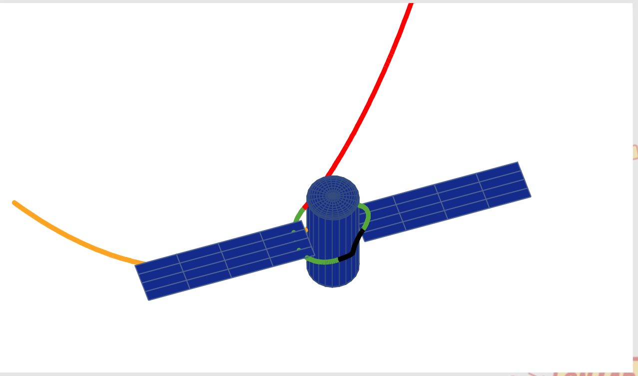
Mission Schedule

1. Parking Orbit (PO): relative free-dynamics around the target to acquire preliminary information regarding target's state (shape, attitude, angular motion, viewpoints)
2. Approaching Phase (AP): the chaser moves toward the first viewpoint following an optimized trajectory
3. Observation Phase (OP): remaining in fixed position relative to the target, the chaser performs visual inspection of its surface by means of a camera mounted on a robotic arm
4. Transfer Branch (TB): transfer to the next viewpoint following an optimized, collision-free path
5. Return Phase (RP): phases 3-4 are repeated until all the viewpoints have been visited; then, the chaser returns to the PO





GNC Architecture

GUIDANCE
(Trajectory design)

PERFORMANCE & SAFETY

NAVIGATION
(State Estimation)

ACCURACY

CONTROL
(Trajectory Tracking)

PRECISION & SAFETY

MISSION ACCOMPLISHMENT

Dynamics: Tschauner-Hempel Equations

$$\ddot{x} = 2\omega\dot{y} + \omega^2 x + \dot{\omega} y - \mu_\oplus \frac{r_0 + x}{r_1^3} + \frac{\mu_\oplus}{r_0^2} - \boxed{D_{1,x} + D_{0,x} + J_{1,x} - J_{0,x}} + \boxed{u_x}$$

$$\ddot{y} = -2\omega\dot{x} + \omega^2 y - \dot{\omega} x - \mu_\oplus \frac{y}{r_1^3} - \boxed{D_{1,y} + D_{0,y} + J_{1,y} - J_{0,y}} + \boxed{u_y}$$

$$\ddot{z} = -\mu_\oplus \frac{z}{r_1^3} - \boxed{D_{1,z} + D_{0,z} + J_{1,z} - J_{0,z}} + \boxed{u_z}$$

0 = target
1 = chaser

Target on an elliptical orbit

Non Linear equations

Drag and J_2 perturbations

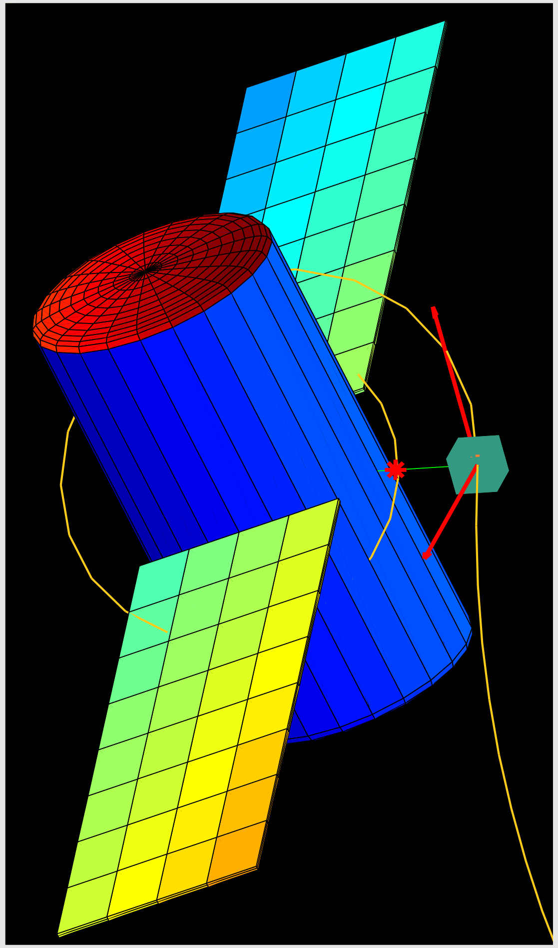
Control

Guidance: Desired Trajectory Computation

The chaser follows an optimized trajectory during AP and TBs, while it keeps a fixed position with respect to the target during OPs

Trajectory Optimization for AP and TBs

- Minimization of the maneuver Delta V (propellant mass)
- Inverse optimization method
- Collision Avoidance
- Choice of next viewpoint on a minimum Delta V basis



Keeping during OPs

- Visual Inspection operation requires a relative still position in order to operate the robotic arm
- Chaser in phase with the target's rotation (i.e. keeps its position relative to the target)

Guidance: Trajectory Definition

Inverse Method: polynomial parameterization

1. Express the objective function by means of state components

$$\Delta V = \int_{t_0}^{t_f} \sqrt{u_x^2 + u_y^2 + u_z^2}\; dt$$

$$\mathbf{u} = \boxed{f\left(\boldsymbol{\rho},\ \dot{\boldsymbol{\rho}},\ \ddot{\boldsymbol{\rho}}\right)}$$

Depends on the chosen dynamical model

2. Parameterize the state. Polynomials of order 5 have been chosen

$$\boldsymbol{\rho}(t) = \sum_{k=0}^{N} \boldsymbol{\alpha}_k t^k$$

3. Analitically satisfy initial and final constraints

$$\boldsymbol{\rho}\left(t_{0/f}\right) = \sum_{k=0}^{N} \boldsymbol{\alpha}_k\, t_{0/f}^{k} = \boldsymbol{\rho}_{0/f}$$

$$\dot{\boldsymbol{\rho}}\left(t_{0/f}\right) = \sum_{k=1}^{N} \boldsymbol{\alpha}_k\, t_{0/f}^{k-1} = \dot{\boldsymbol{\rho}}_{0/f}$$

4. Express ΔV as a function of free parameterization coefficients and vary them to find a minimum

$$\Delta V = f\left(\alpha_k\right)$$

Non-Linear Constraints: Collision Avoidance

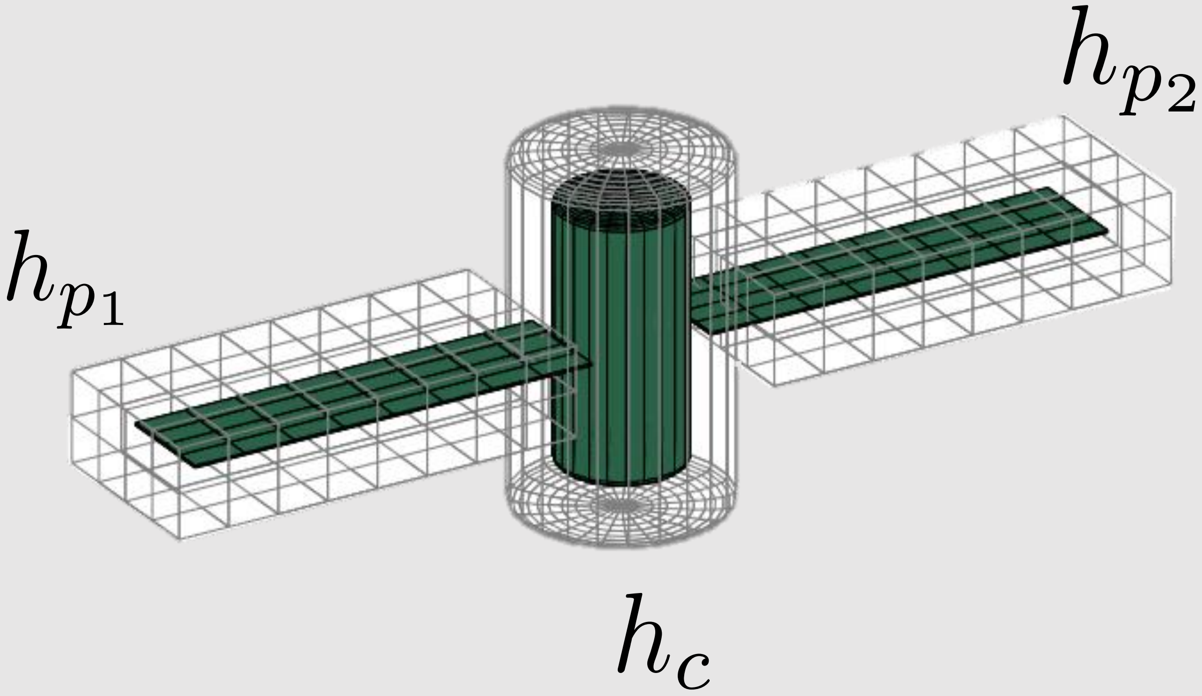
Keep Out Coat (KOC)

$$h\left(x,y,z\right)=\left(\frac{x-x_c}{a+\delta}\right)^{n_1}+\left(\frac{y-y_c}{b+\delta}\right)^{n_2}+\left(\frac{z-z_c}{c+\delta}\right)^{n_3}-1$$

Superellipsoid

Properties of a superellipsoid function:

- *$h = 0$ on the surface*
- *$h > 0$ outside the surface*
- *$h < 0$ inside the surface*



The safety zone shape is created as a multiplication of superellipsoids, which still retains the above properties

$$l\left(x,y,z\right)=h_c\,h_{p_1}\,h_{p_2}$$

Coat shape

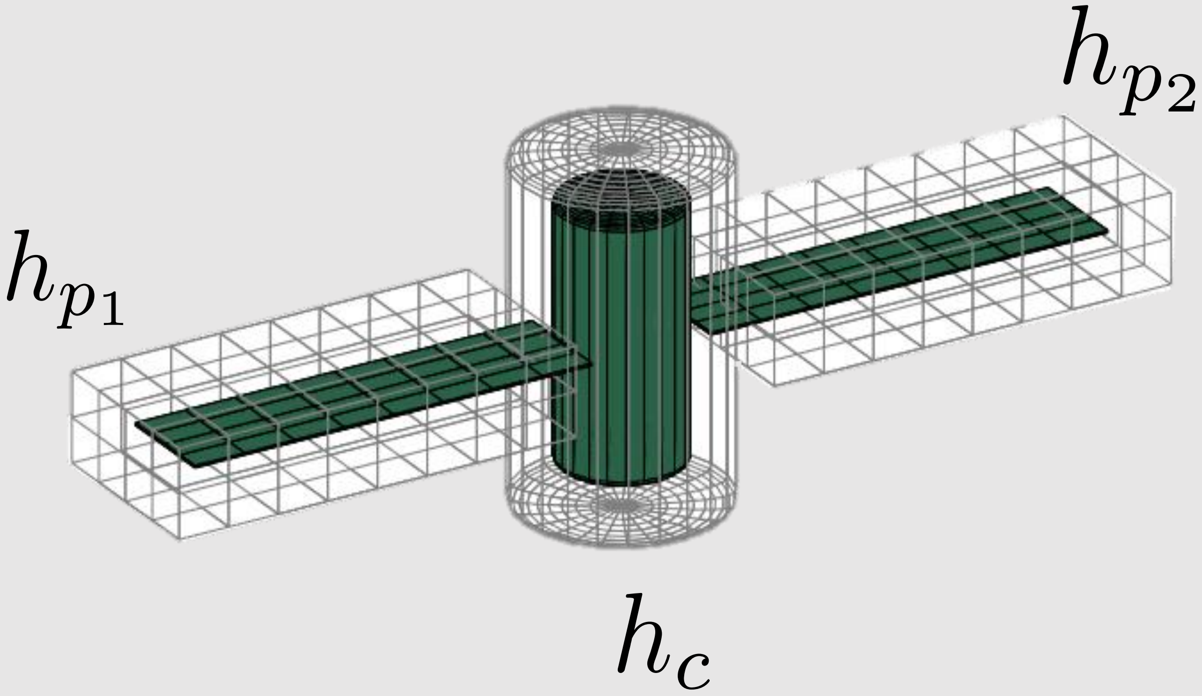
Non-Linear Constraints: Collision Avoidance

Keep Out Coat (KOC)

- When designing the relative trajectory we want to avoid collisions between chaser and target $\Longrightarrow$ ***we design a trajectory which does not pass in the KOC***
- The analytical condition that assures no passage in the KOC is (recalling superellipsoid properties):

$$l\left(\boldsymbol{\rho}^{BODY}(t)\right) > 0$$

Which means that the chaser's center of mass never stays inside the safety shape



Navigation: Unscented H-Infinity Filter

- Differently from a Kalman filter approach (minimum mean covariance), **UHF is a worst case minimization filter (minmax filter),** meaning it minimizes the following cost function

$$J = \frac{\sum_{k=0}^{N-1} \| \boldsymbol{x}_k - \hat{\boldsymbol{x}}_k \|^2}{\| \boldsymbol{x}_0 - \hat{\boldsymbol{x}}_0 \|^2 + \sum_{k=0}^{N-1} \left(\| \boldsymbol{w}_k \|^2 + \| \boldsymbol{v}_k \|^2 \right)} \quad \Longrightarrow \quad \hat{P}_k = \left(\left(\tilde{P}_k - K_k \hat{P}_k^{yy} K_k^T \right)^{-1} \boxed{- \frac{1}{\eta_k} I_L} \right)^{-1}$$

- UHF is a conservative filter, as it increases the covariance at each step
- A conservative filter is more suitable in proximity operations, where collisions must be avoided
- Relative range, azimuth and elevation angles are measured by sensors and used inside the UHF

Control: PD/ PD + feedforward

Two control strategies are compared:

- Proportional Derivative (PD) control, where the gains are computed by means of a Linear Quadratic Regulator (LQR)

$$\mathbf{u} = -K\left(\hat{\mathbf{x}} - \mathbf{x}_{des}\right)$$

- PD with the addition of a FeedForward (FF) term

$$\mathbf{u} = \ddot{\mathbf{x}}_{des} - K\left(\hat{\mathbf{x}} - \mathbf{x}_{des}\right)$$

Simulation Scenario: Parameters

Initial and orbital parameters

Quantity	*Values*
Coe (a, e, i, Ω, ω, υ_0)	7500, 0.1, 99.84°, 150°, 100°, 0°
Initial Relative Position	100 m, 0 m, 100 m
Initial Relative Velocity	0 m/s, -0.23 m/s, 0 m/s
Initial Target's Angular Velocity	0.1 deg/s, 0.2 deg/s, 0.3 deg/s
Keep Out Coat Safety Offset	1 m

Target Dimensions

Quantity	*Values (m)*
r_{cil}	3
h_{cil}	12
l_{pan}	20
w_{pan}	5
h_{pan}	0.1

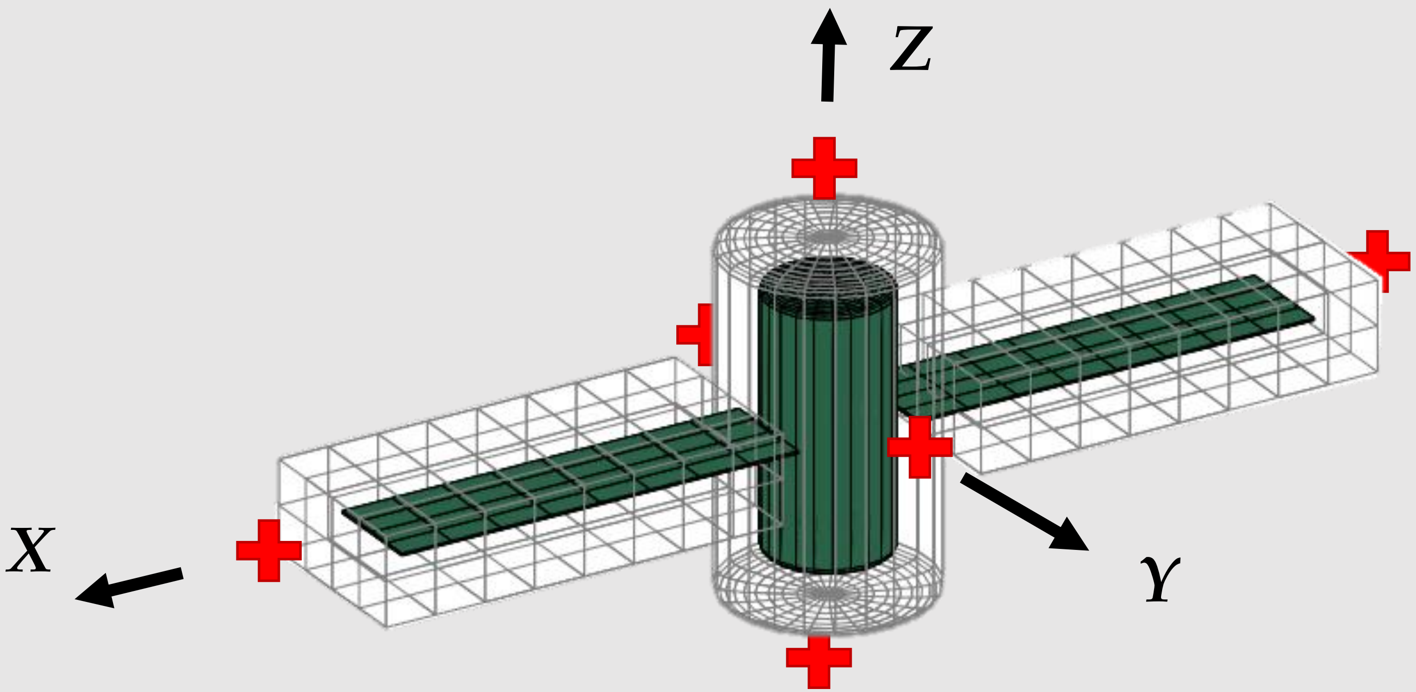
Mission Time Schedule

	PO	*AP*	*OP*	*TB*	*RP*
Time (s)	3230 (T/2)	5810	300	600	5810

Simulation Scenario: Viewpoints

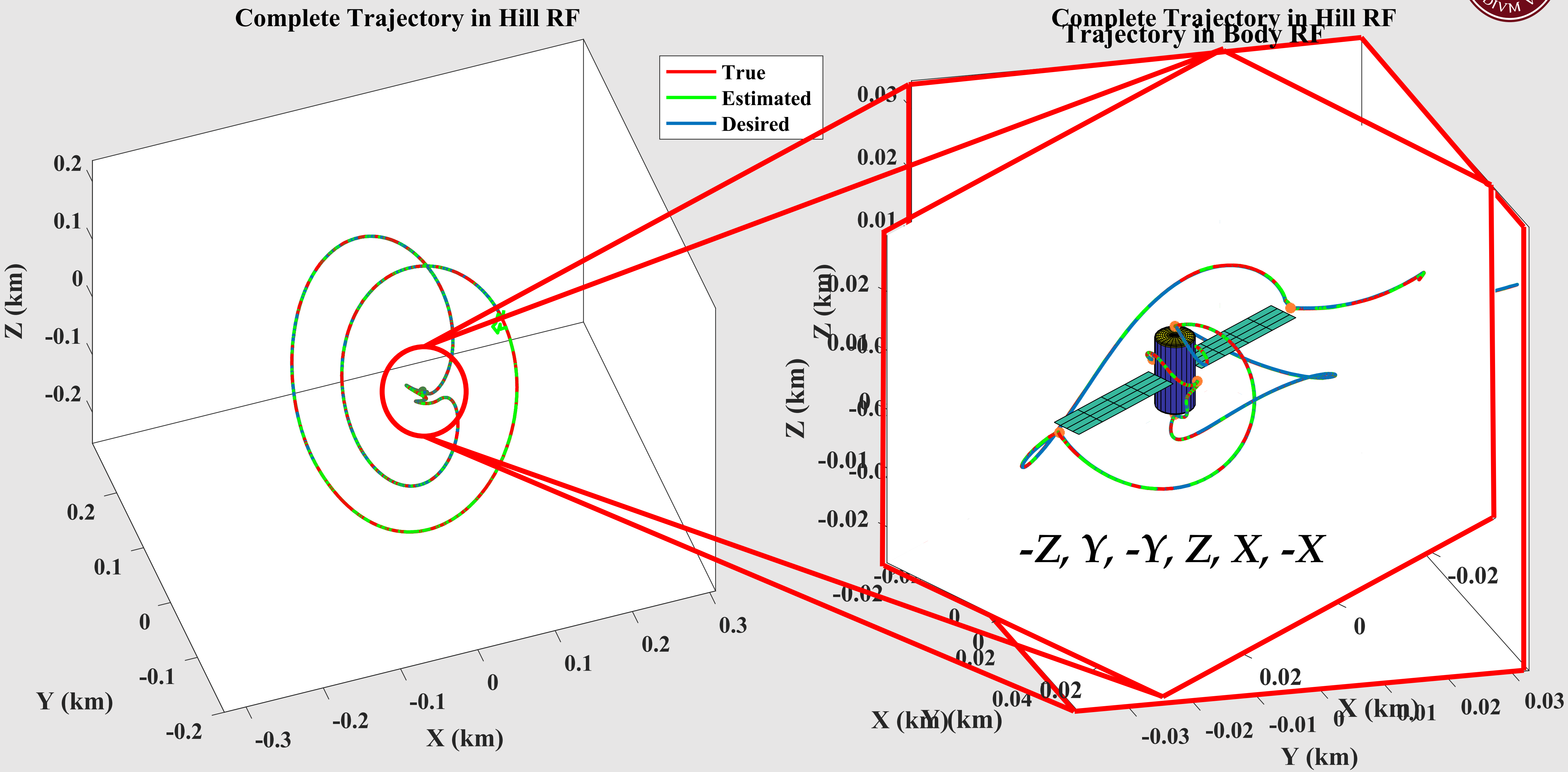
6 viewpoints have been identified as sufficient to visually assess the presence of failures on this particular target's shape

	X	- X	Y	- Y	Z	- Z
Distance from center of mass (m)	24.5	- 24.5	4.5	- 4.5	7.5	- 7.5



+1 meter offset has been used for additional safety

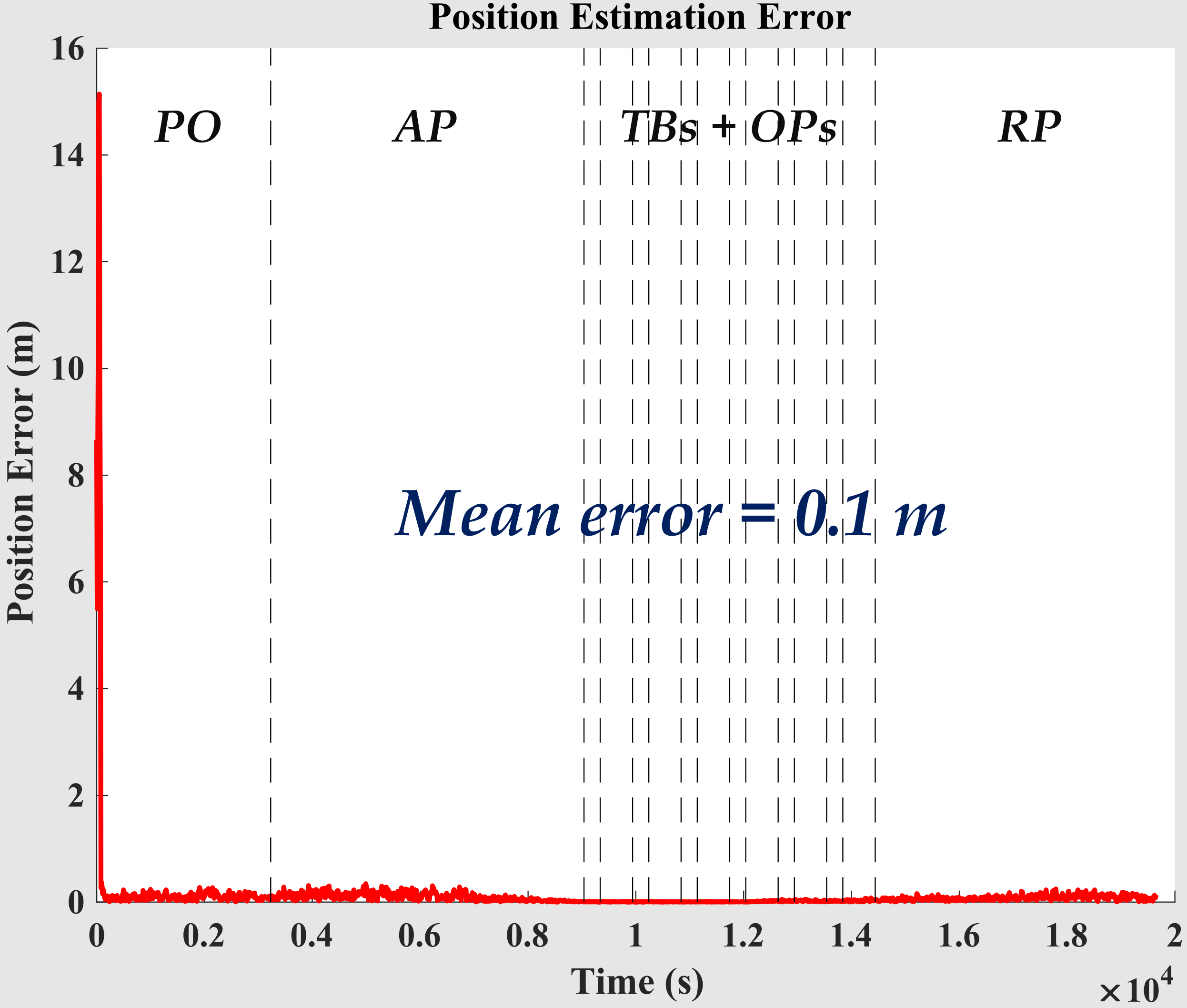
Simulation Scenario #1: Results



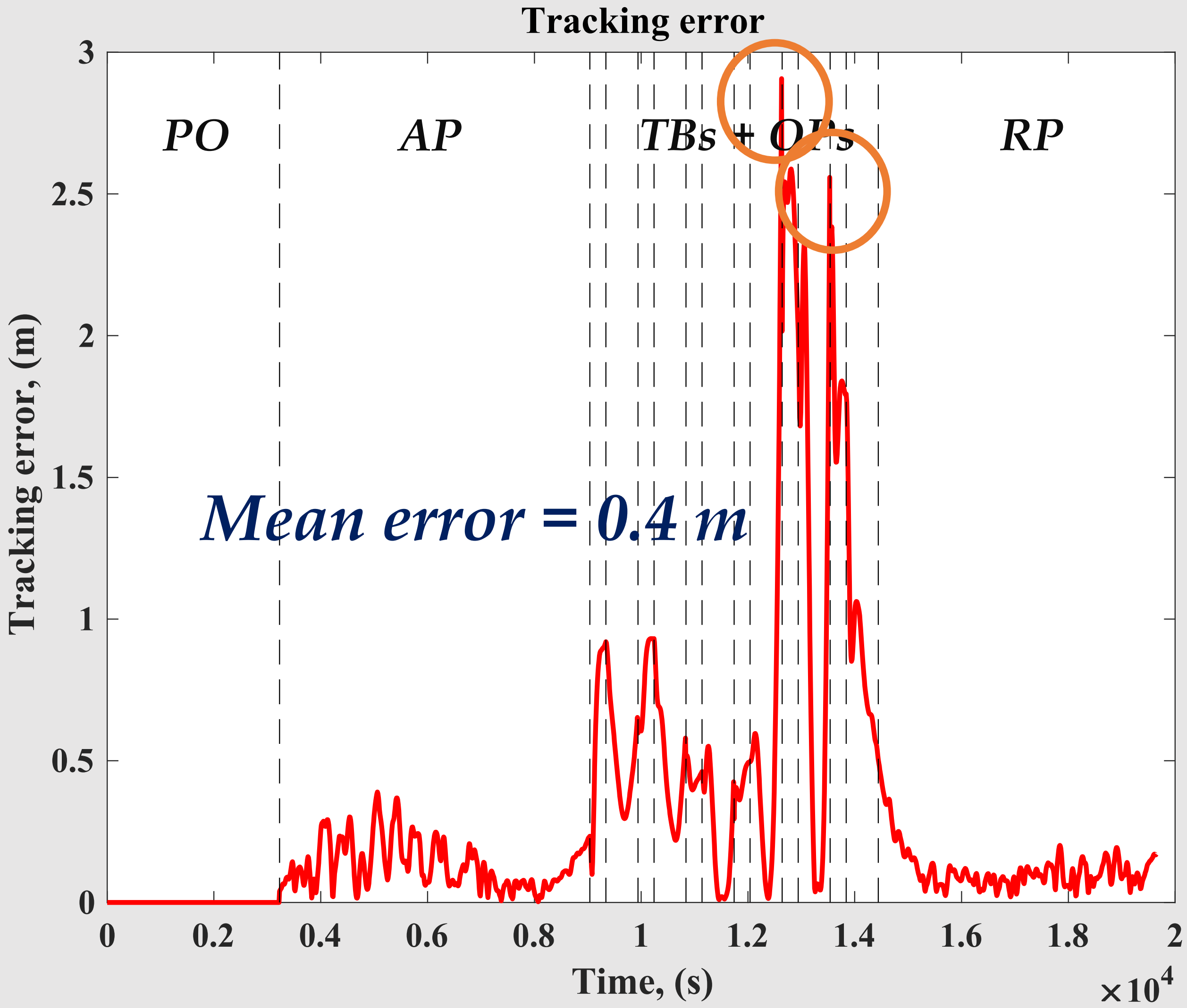
Simulation Scenario #1: Results

UHF and PD Control $\Longrightarrow$ $\Delta V = 2.52\ m/s$

True position – estimated position



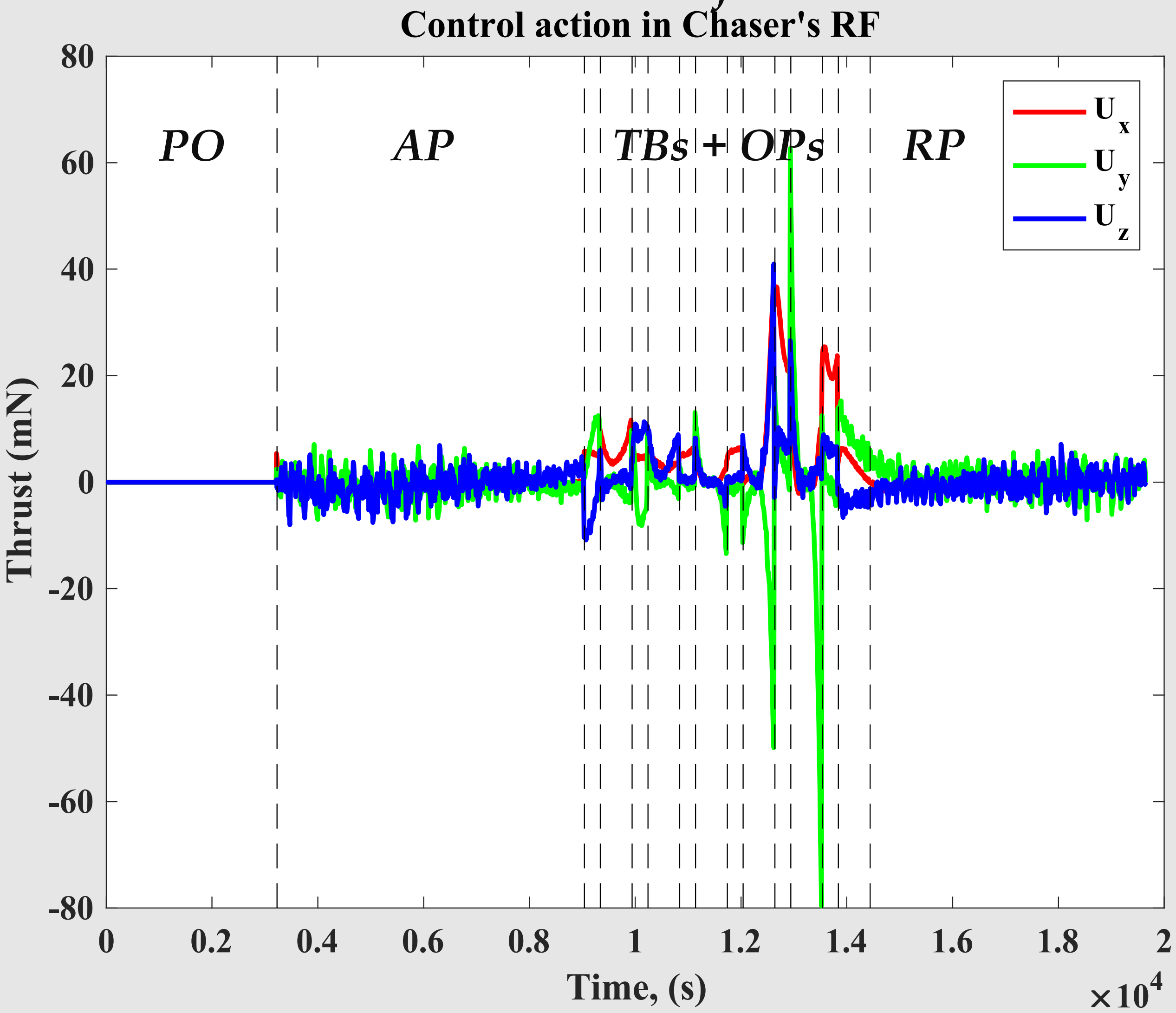
True position – desired position



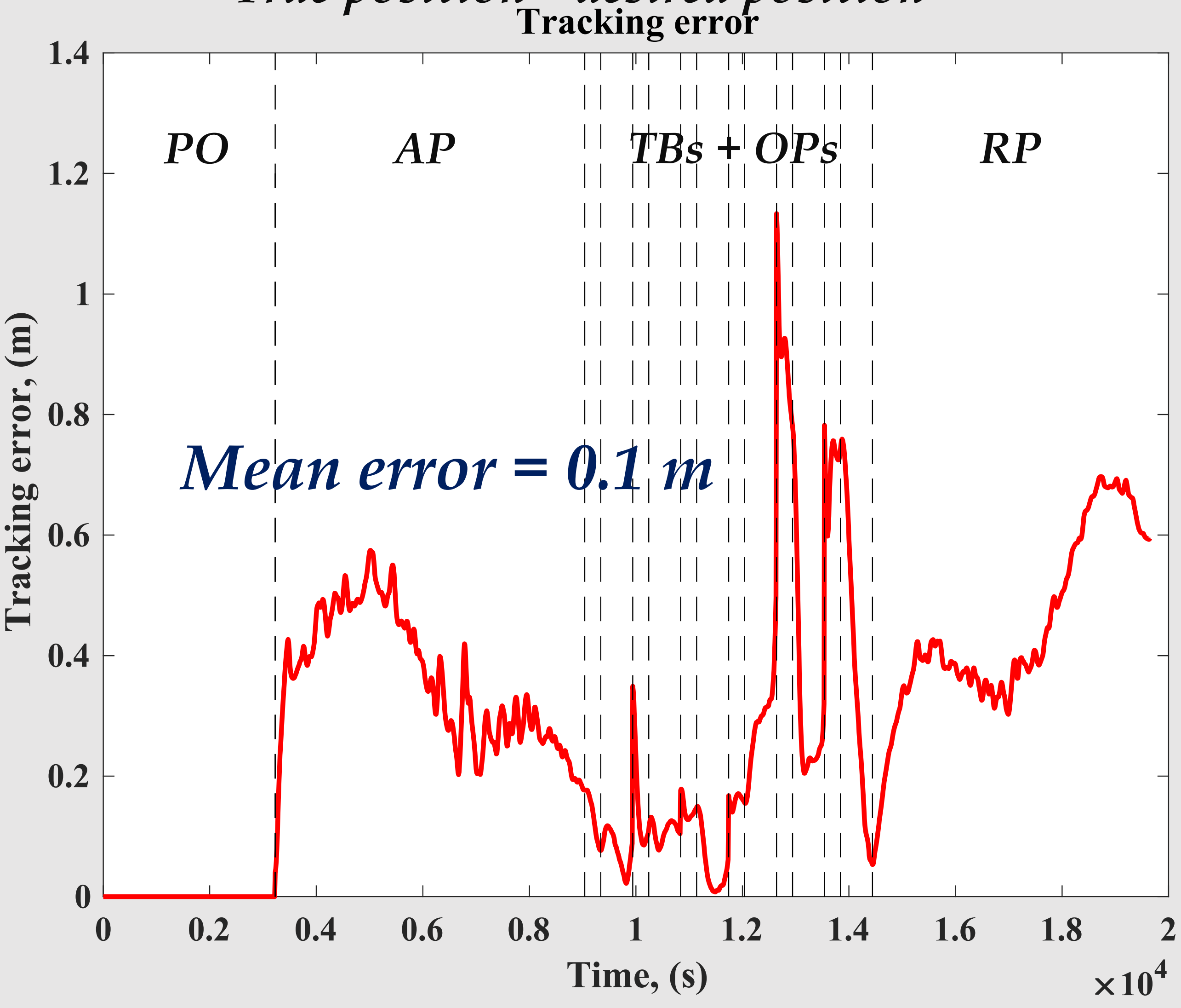
Simulation Scenario #2: Results

UHF and PD+FF Control $\Longrightarrow \Delta V = 2.34\ m/s$

Control Profile



True position – desired position



Final Remarks

A close visual inspection of an uncrontrolled, freely-tumbling satellite can be safely accomplished by means of the proposed mission profile

- The guidance block always provides an optimized, collision-free reference trajectory, with an associated relatively low Delta V (~ m/s)
- The navigation block (UHF) has proven to be robust and accurate in all tested cases

Drawbacks and possible improvements

- Tracking error's peaks of 1.3 meters cannot be reduced any further since a linear control strategy has been used in non-linear dynamics. Still, these errors will not cause mission any failure since the safety offset has been set to 2 meters and the error is along-track
- A non-linear control strategy would diminish tracking error and guarantee a preciser visual inspection of the target
- Viewpoints determination should be made fully automatized

Thanks for your attention

Backup Slides

Dynamics: Perturbations

Earth Centered Inertial

$$D^{ECI} = -\frac{1}{2m} C_D A \varrho v_{rel}^2 \hat{\mathbf{v}}_{rel}$$

$$J^{ECI} = -\left(\frac{3}{2} J_2 \mu_\oplus \frac{R_\oplus^2}{r^4}\right) \begin{bmatrix} \left(1 - 5\frac{r_z^2}{r^2}\right) \frac{r_x}{r} \\ \left(1 - 5\frac{r_z^2}{r^2}\right) \frac{r_y}{r} \\ \left(3 - 5\frac{r_z^2}{r^2}\right) \frac{r_z}{r} \end{bmatrix}$$

Hill Reference Frame

$$D^{Hill} = {}^{Hill}\mathcal{R}_{ECI} \; D^{ECI}$$

$$J^{Hill} = {}^{Hill}\mathcal{R}_{ECI} \; J^{ECI}$$

Attitude Dynamics: Free-Tumbling Target

- 3-axes, freely tumbling target
- Earth's gravity gradient taken into account
- Attitude kinematics written with respect to Hill reference frame

$\Longrightarrow$ Body-to-Hill $\,^{Hill}\mathcal{C}_{Body}$ rotation matrix can be computed $\Longleftarrow$

$$\dot{\boldsymbol{\omega}}_{B/I} = \mathcal{I}^{-1}\left(-\boldsymbol{\omega}_{B/I} \times \mathcal{I}\boldsymbol{\omega}_{B/I} + 3\frac{\mu_{\oplus}}{r_0^3}\hat{\mathbf{r}}_0 \times \mathcal{I}\hat{\mathbf{r}}_0\right)$$

$$\boldsymbol{\omega}_{B/H} = \boldsymbol{\omega}_{B/I} - \boldsymbol{\omega}_{H/I}$$

$$\dot{\mathbf{q}}_{B/H} = \frac{1}{2}\Omega\left(\boldsymbol{\omega}_{B/H}\right)\mathbf{q}_{B/H}$$

Mission Schedule

In order to correctly accomplish the target' s inspection, the following phases have been identified as relevant:

1. Parking Orbit (PO): the chaser is in a free-dynamics around the target to acquire preliminary information regarding target's state;
2. Approaching Phase (AP): starting from the PO, the chaser moves toward the first viewpoint following an optimized trajectory;
3. Observation Phase (OP): remaining in fixed position relatively to the target, the chaser performs visual inspection of target's surface by means of a camera mounted on a robotic arm;
4. Transfer Branch (TB): the chaser transfers to the next viewpoint following an optimized, collision-free path;
5. Return Phase (RP): phases 3-4 are repeated until all the viewpoints have been visited. Then, the chaser returns to the PO.

Mission Schedule