POLITECNICO MILANO 1863

DIPARTIMENTO DI SCIENZE E TECNOLOGIE AEROSPAZIALI

6th International Conference on Astrodynamics Tools and Techniques

17th March 2016 – Darmstadt, Germany

GNC TECHNIQUES FOR PROXIMITY MANOEUVRING WITH UNCOOPERATIVE SPACE OBJECTS

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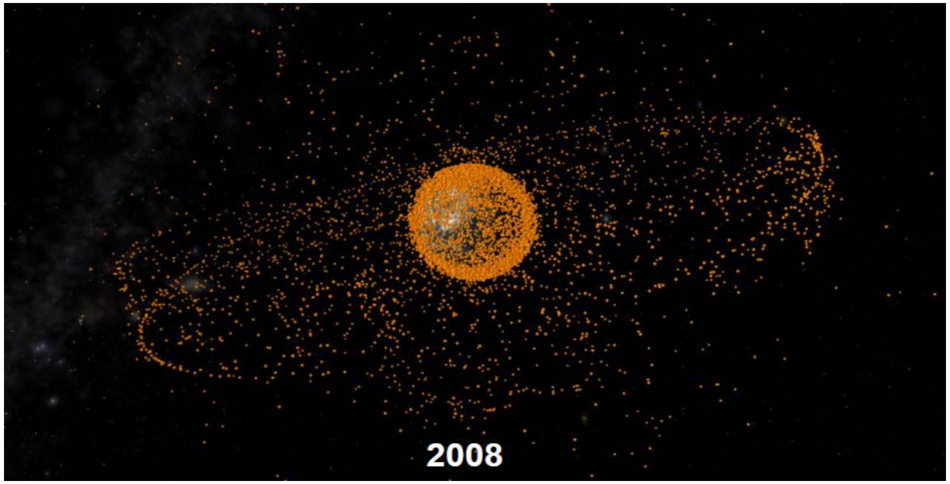
Background – ACTIVE DEBRIS REMOVAL



Credits ESA

- 6000 satellites into orbit, <1000 still operational
- **LEO and GEO orbits**
- ADR focused on massive elements, effective if 10 objects removed per year

- Active servicer s/c
  - **Non-cooperative tumbling target**
  - Approach & Docking
  - De/Re-Orbiting
- **GNC challenges – autonomy**
- Preferred strategies for ADR:
  - **ROBOTIC ARM** - rigid connection
  - **THERED-NET** - flexible connection

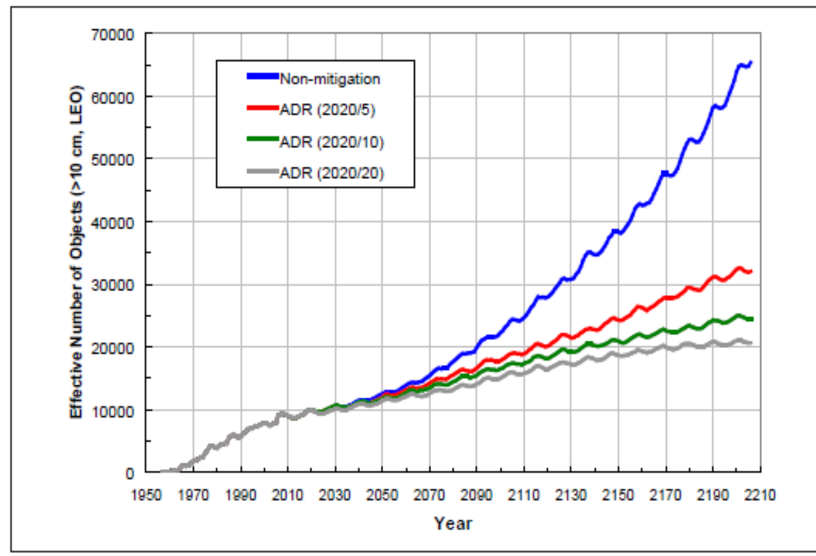
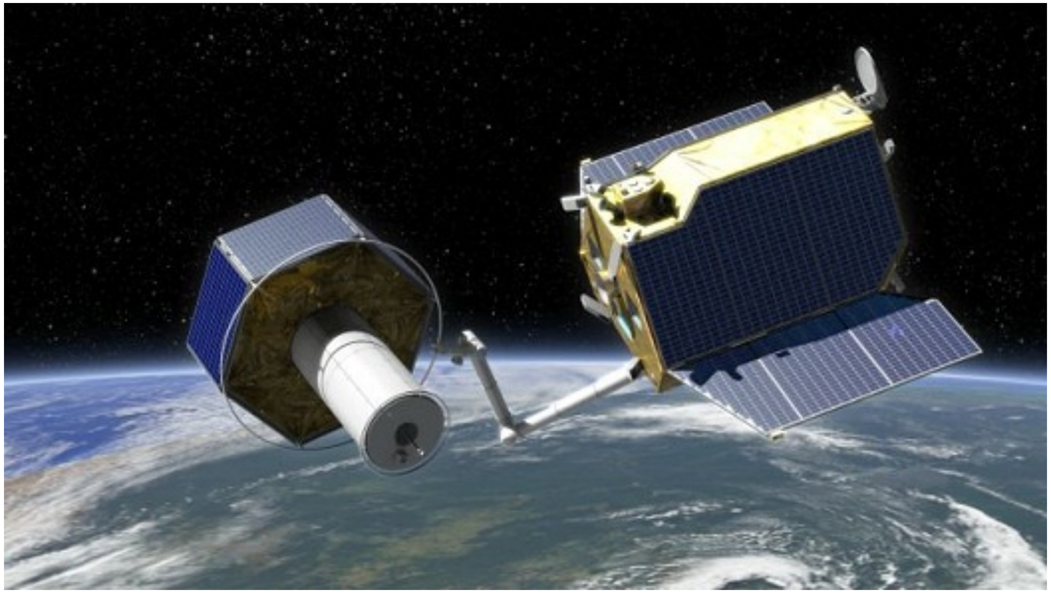


Figure 1. LEGEND-simulated LEO debris populations (objects 10 cm and larger) between 1957 and 2006 (historical), and between 2007 and 2206 (future projection). Each curve represented the average of 100 Monte Carlo runs.

Credits Liou, NASA, IAC 2007

Background – ON ORBIT SERVICING



DEOS: credits DLR

- Active servicer s/c
  - **Partially cooperative target**
  - Approach & Docking
  - Refuelling
  - Repairing/Maintenance
- **GNC challenges – autonomy**
- Strategy for OOS:
  - **ROBOTIC ARM** with end-effector
  - **Grippers/Clamping** mechanisms

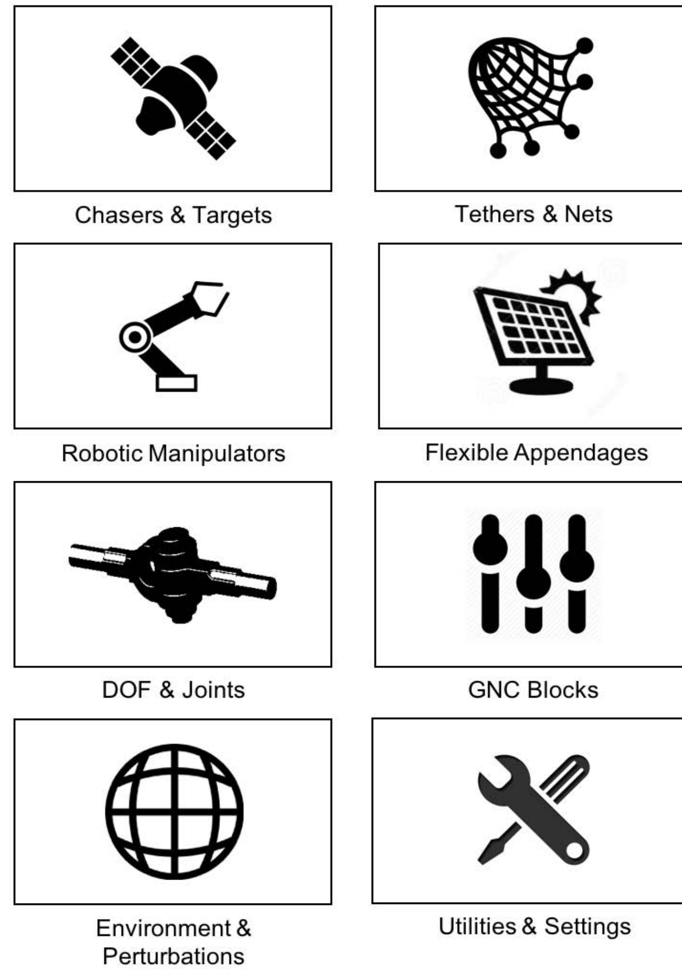
RESEARCH OBJECTIVES

1. Develop **fast & reliable dynamics models** for ADR and OOS system and GNC design
2. Implement **GNC laws** for **proximity manoeuvring** to increase level of autonomy
3. **Validating dynamics** and **test control** – experimental activities and HIL

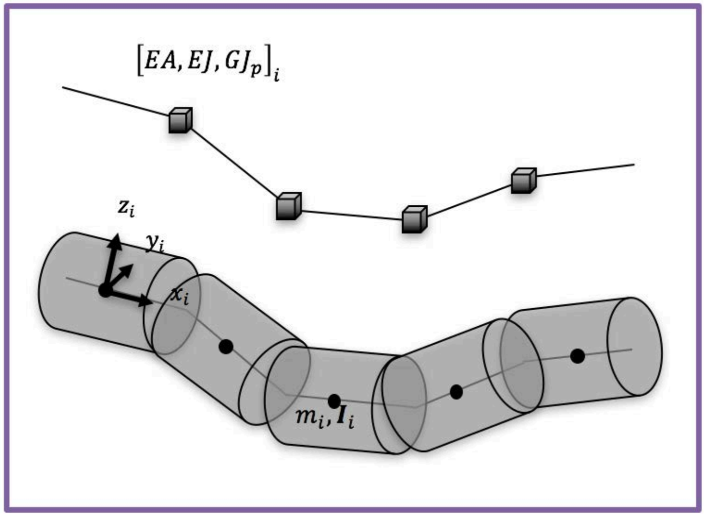
Table of Contents

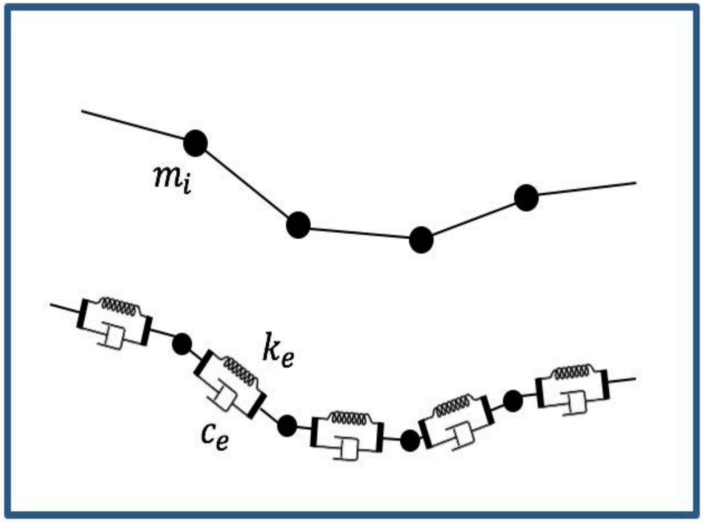
ADR/OOS Simulation Environment

- Fast simulation environment to support GNC design
    - Born for ESA's study **MUST** [*Benvenuto, 2014*]
    - Further upgrades after activity
- Fully integrated in Matlab/Simulink
    - **Simulink libraries**
    - **SimMechanics**
- Describe 6-DOF orbital and attitude bodies dynamics with:
    - Flexible **tethers/nets**
    - **Robotic manipulators**
    - Flexible appendages and sloshing
    - Environment and perturbations
    - GNC blocks
- Tool **validated** by means of benchmarking and **experimental activities**



ADR/OOS Simulation Environment

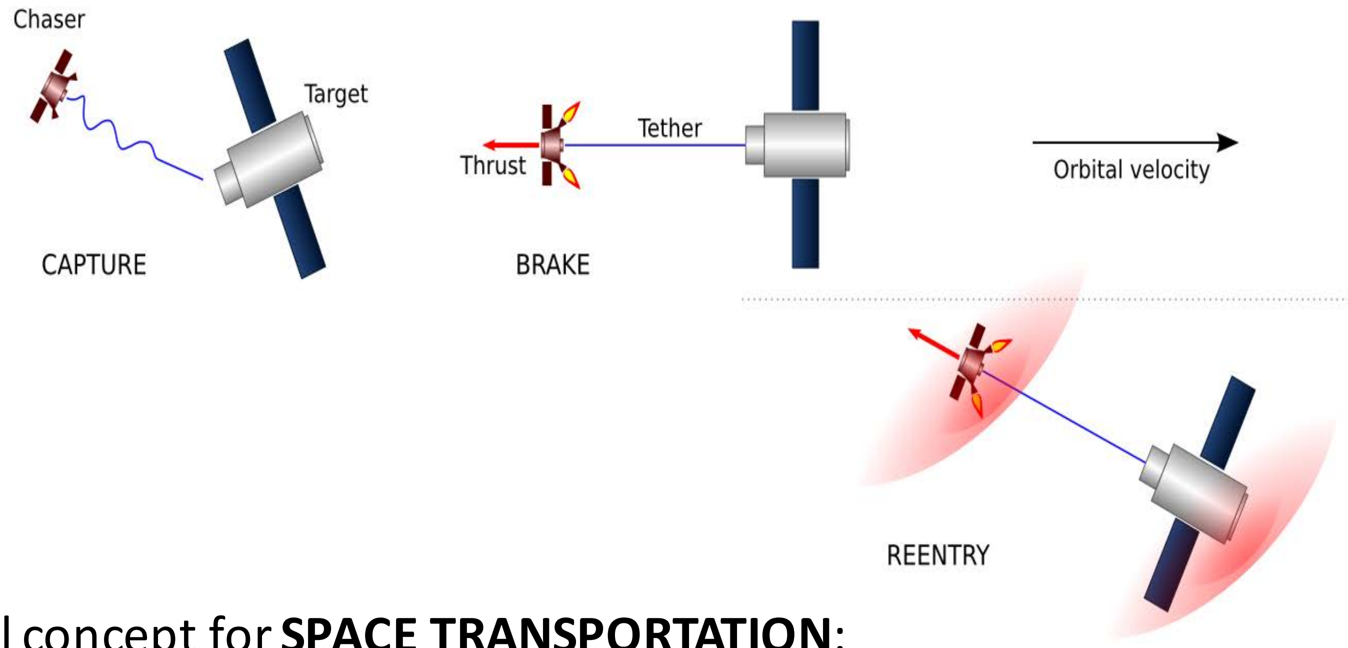




Flexible models based on **lumped parameters methods**

- Model **higher order modes**
- Approximate flexing/whipping - arbitrary number of discretizing elements
- **Fast computations**
- Accounting for different viscoelastic laws
- **Parametric**, different configurations

Tethered Tug Scenario



- Original concept for **SPACE TRANSPORTATION**:
  - Exploitable for Active Debris Removal
  - Passive target connected to an active chaser, its thrusters exciting stack
  - **Fixed-length flexible tethers**
  - V-bar alignment configuration - **unstable**
  - **Fast dynamics**
  - Target mass > chaser mass

Tethered Tug Scenario

Critical modes and instabilities

- **Whiplash effects**: leading to difficult control recovery, (necessary tether tensioning and stabilization)
- **Bounce-Back effects:** post burn phase-slack tether and possible collisions due to residual tension
- Tether entanglement and breakage: avoid free motion and slack tether
- Atmospheric re-entry: chaser control authority holds till a minimum altitude where drag on target prevails

Stack G&C

Closed loop:

Stabilization + Bang-off + post-burn recovery [*Benvenuto, 2014*]

Tension feedback to reduce bounce-back

Open loop:

Feed-forward shaping of commanded thrust profile [*Jasper, 2014*]

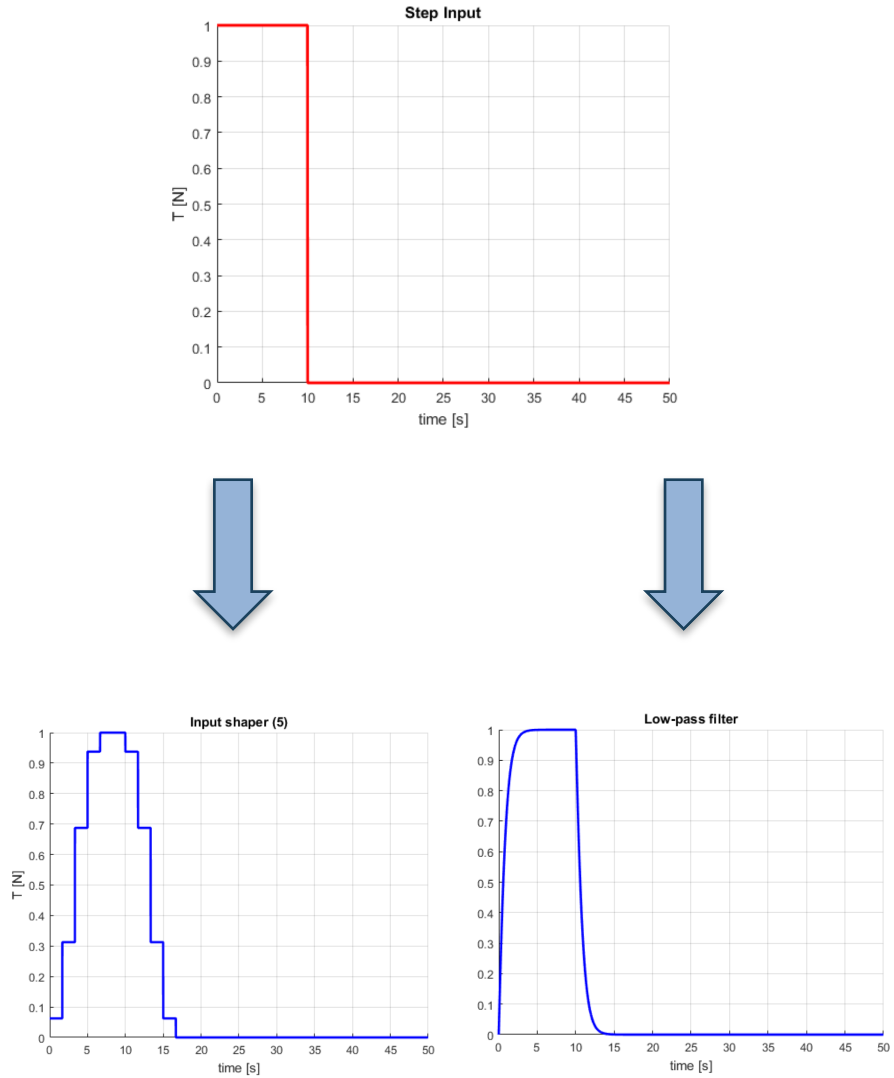
- Input shaping
- Command smoothing/filtering

Closed loop attitude control

Tethered Tug Scenario

Input Shaping

- Signal convolved with series of impulses
- Thrust modified by steps
- Achievable with thrusters' **cluster** (on-off)
- Increased time to obtain same ΔV



Command smoothing

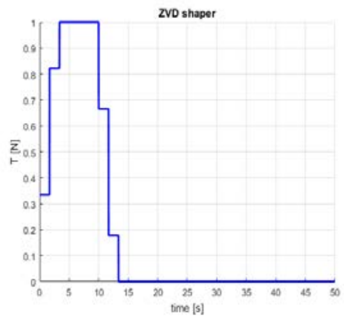
- Signal filtered
- Thrust modified continually
- Need continuous thrust modulation - **throttling**
- Increased time > shapers
- **Robustness to uncertainties** (ω, ξ) > shapers

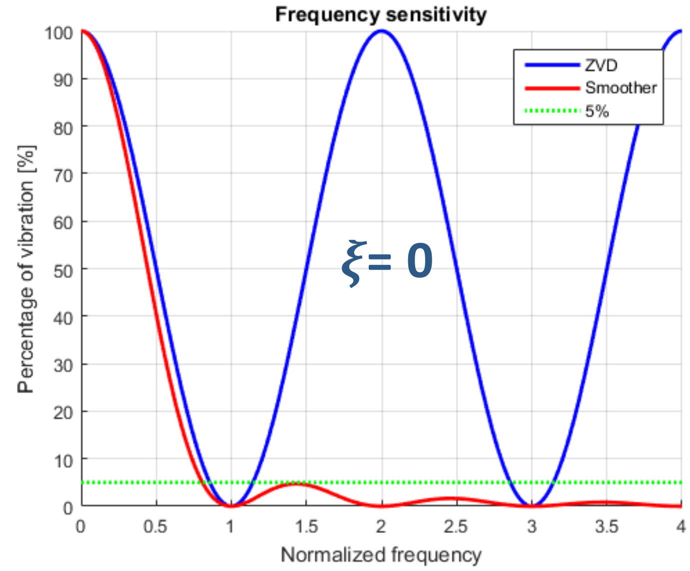
Tethered Tug Scenario

ZVD Shaper

$$\begin{bmatrix} A_i \\ t_t \end{bmatrix} = \begin{bmatrix} \dfrac{1}{1+2K+K^2} & \dfrac{2K}{1+2K+K^2} & \dfrac{K^2}{1+2K+K^2} \\ 0 & 0.5T_d & T_d \end{bmatrix}$$

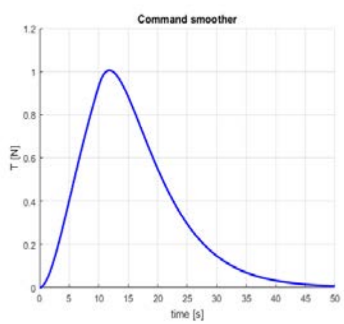
$$K = e^{\left(-\xi\pi/\sqrt{1-\xi^2}\right)}$$

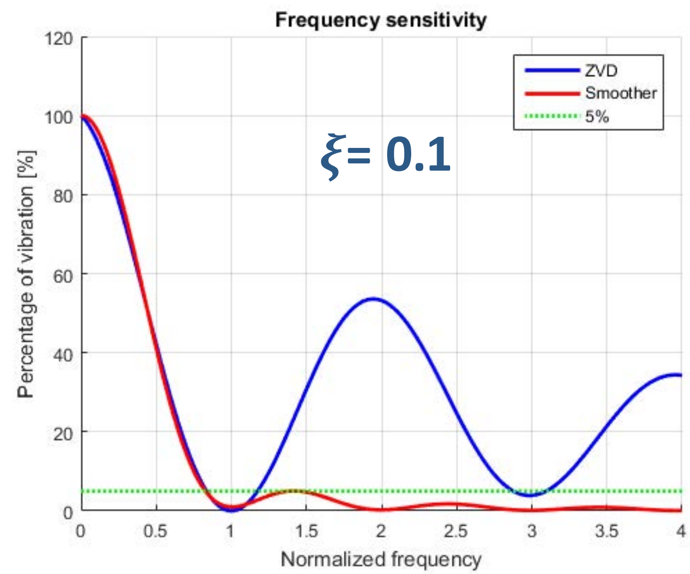




Command Smoother

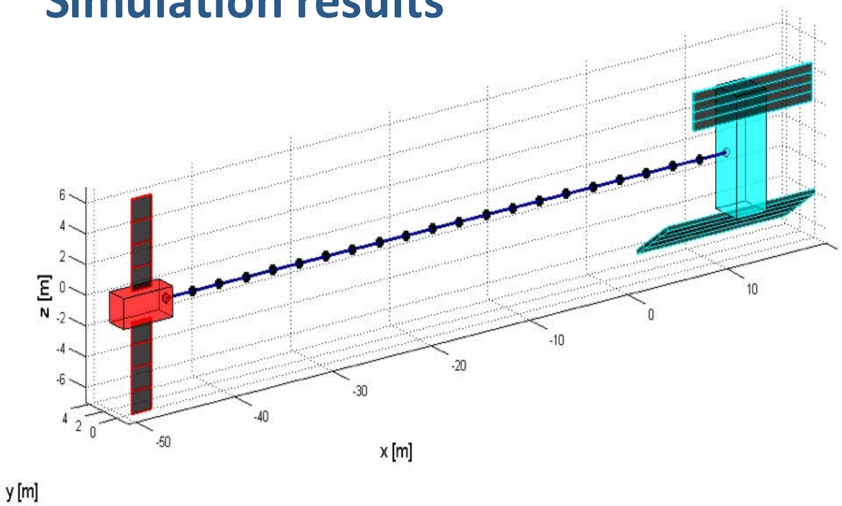
$$G(s) = \frac{\xi^2\omega^2}{(1-M)^2}\frac{(1-K^2e^{-T_d s})^2}{(s+\xi\omega)^2}$$





Tethered Tug Scenario

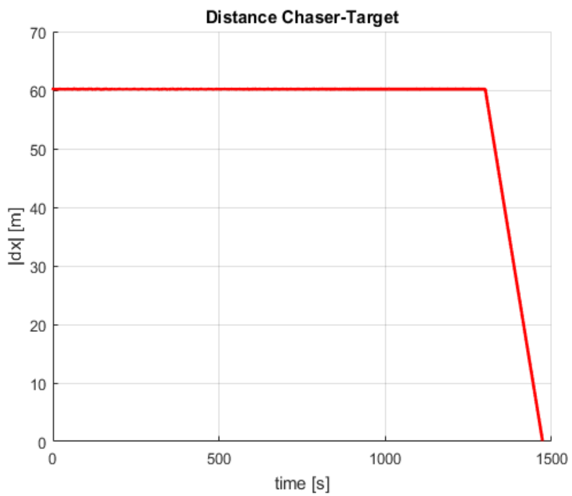
Simulation results



Chaser Mass [kg]	1300
Target Mass [kg]	5000
Initial orbit altitude [km]	600
Thrust [N]	800
Tether Young's modulus [GPa]	32
Tether damping factor [-]	0.1
Tether length [m]	60
Tether diameter [m]	0.003

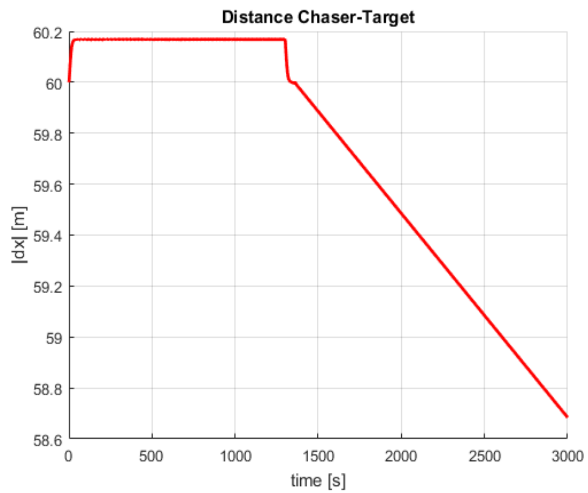
ΔV [m/s]	160
Flight angle at 120 Km [deg]	-1.6

Bang-Off



ZVD Shaper

C - Smoother



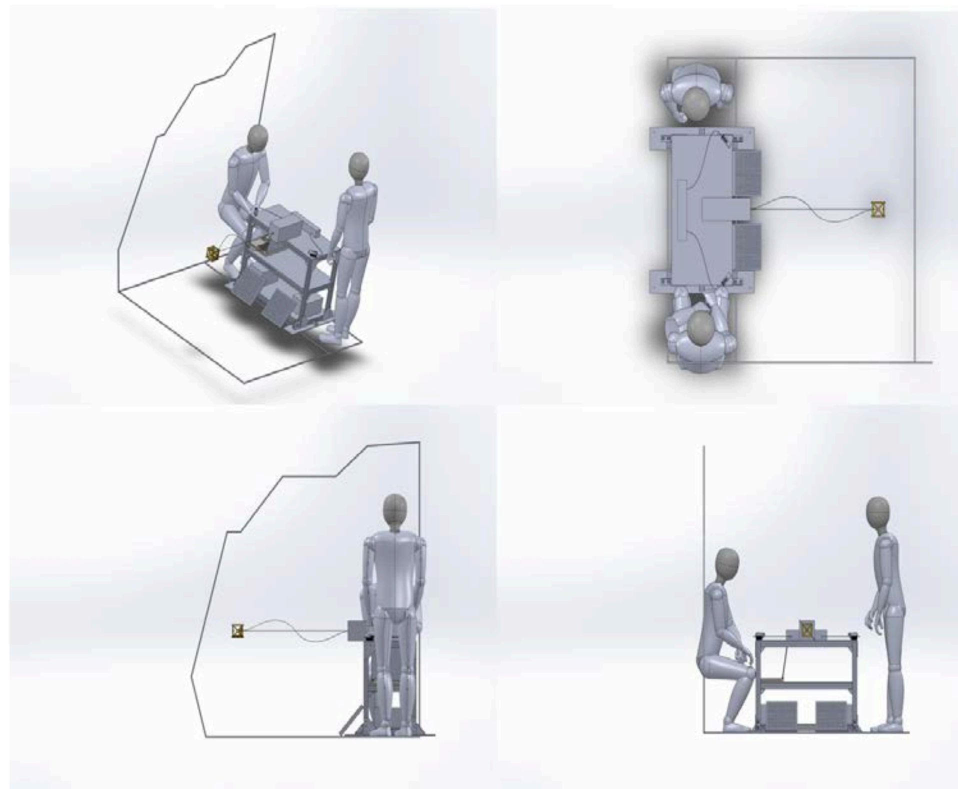
Tethered Tug Scenario

Experimental Microgravity Validation

SatLeash
PoliTethers

fly your thesis!

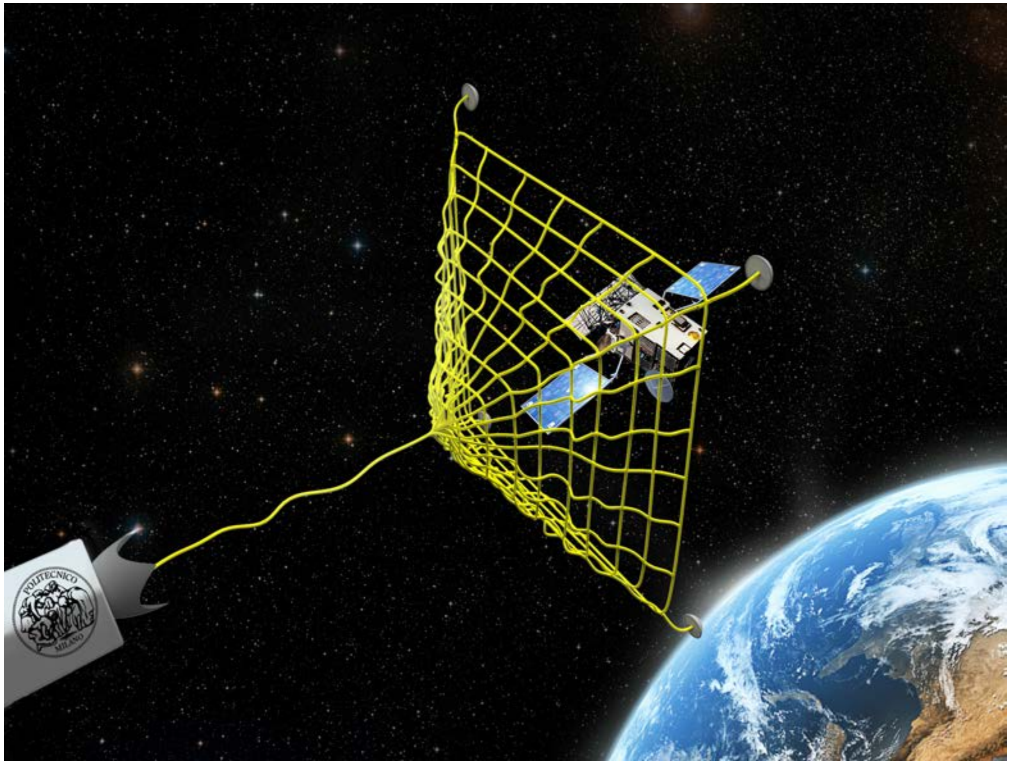
- PoliTethers Team selected for ESA's Education **Fly Your Thesis! 2016**
- **Parabolic flight campaign** October 2016
- Release and retrieval of **tethered floating module**
- Actuator to **simulate thrust profiles**
- Stereo-vision reconstruction + acceleration/tension sensors



Capture Net Scenario

Benefits

- Larger capture distance
- Isotropic loads
- Partially independent from target features (physical and dynamic)
- **Centre of mass alignment with thrust axis not a constraint**
- Scalable device, light payload



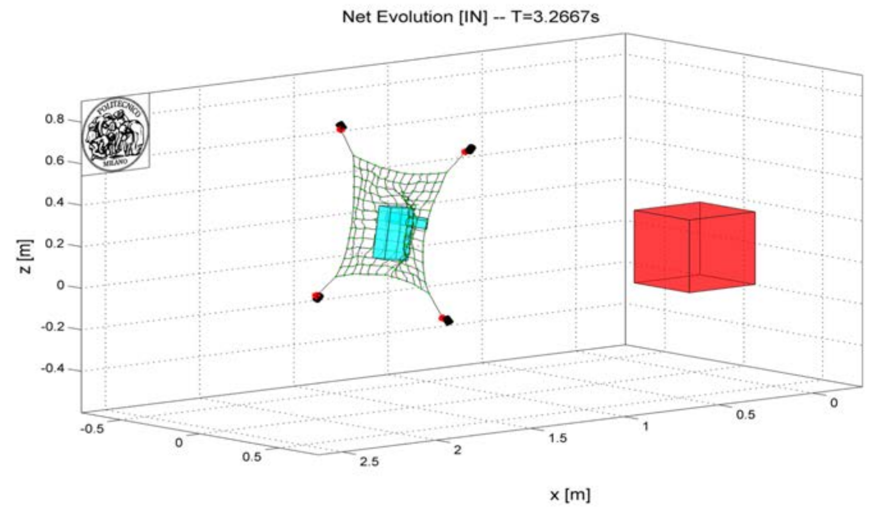
Criticalities

- Passive device (except if controlled bullets)
- Non repeatability - one shot chance
- Difficulty in detecting capture
- Possible slippages: closing device

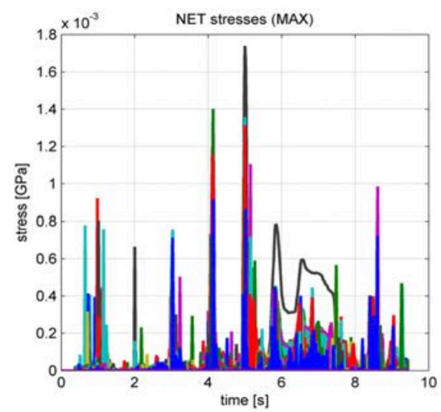
Capture Net Scenario

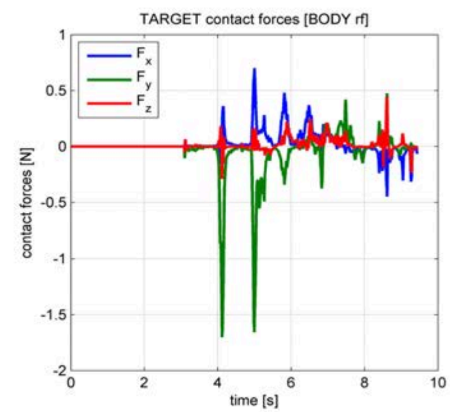
Enhanced modelling

- **Collision detection**
  - Multi-step refinement – computational time
  - Hierarchical bounding boxes
  - Avoid interpenetration
  - Auto-collisions



- **Contact dynamics**
  - Non-linear contact law (H-C)
    - Avoid shock loads
    - Avoid sticking effects
  - Regularized friction law
  - Coefficients determined through lab tests – characterization of mechanical properties





Capture Net Scenario

G&C

- RDV along track

- No reaction compensation at shooting occurrence (limited bandwidth)

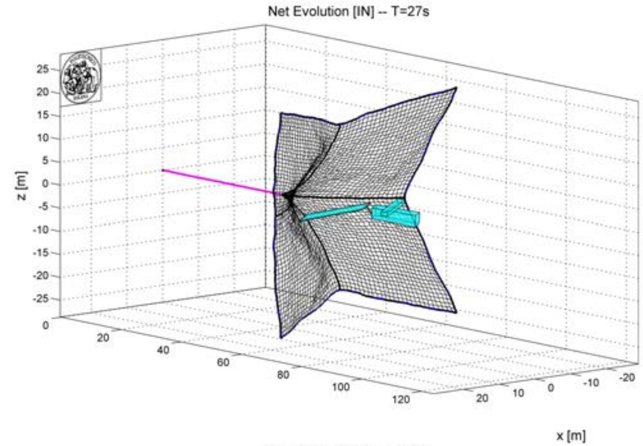
- Chaser attitude controlled (eigenaxis)

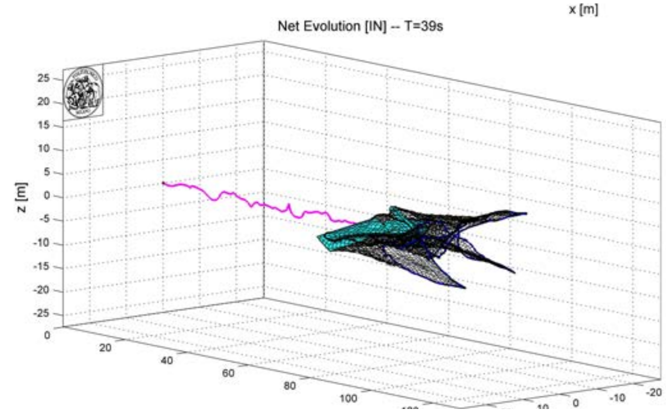
$$u = \omega_C \times I_C \omega_C - D\,\omega_C - K\,q_e$$

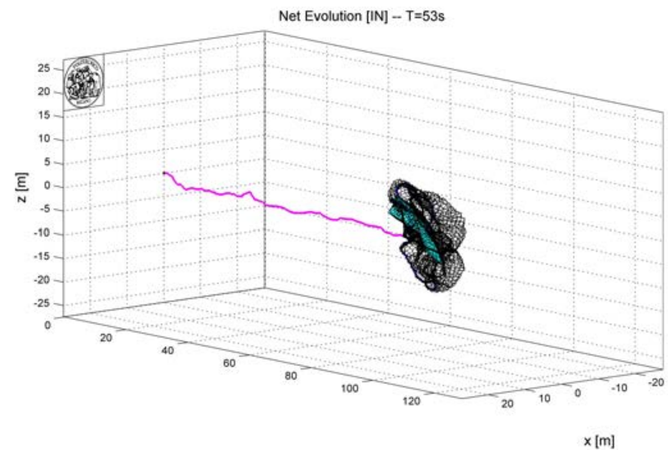
$$K = \omega_{BW}^2 I_C \qquad D = 2\xi\,\omega_{BW} I_C$$

- **Tumbling target passive angular momentum damping**

  Friction damping effect during towing [*Benvenuto, 2015*]







Capture Net Scenario

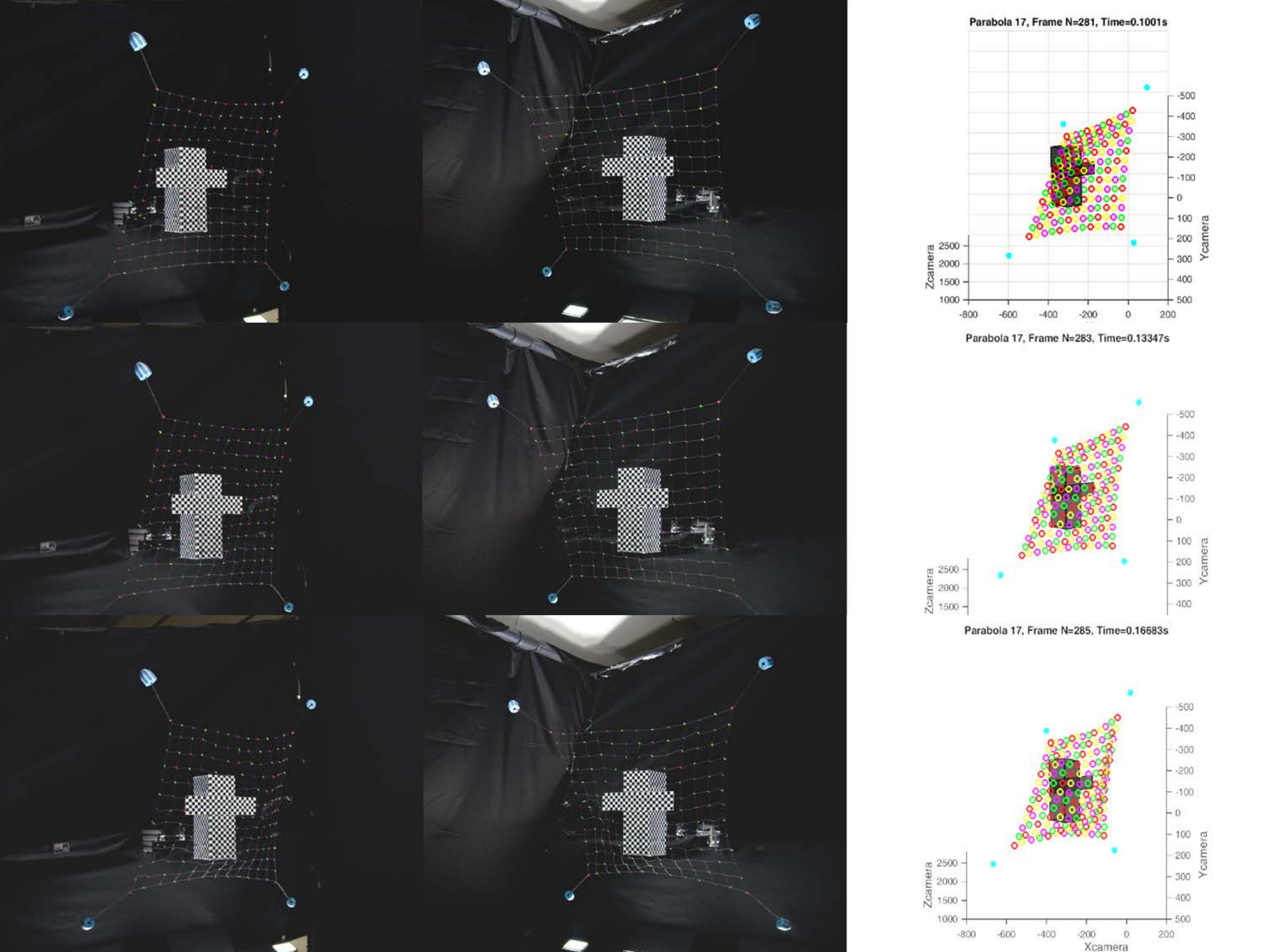
Parabolic flight campaign to validate net flexible model and contact model

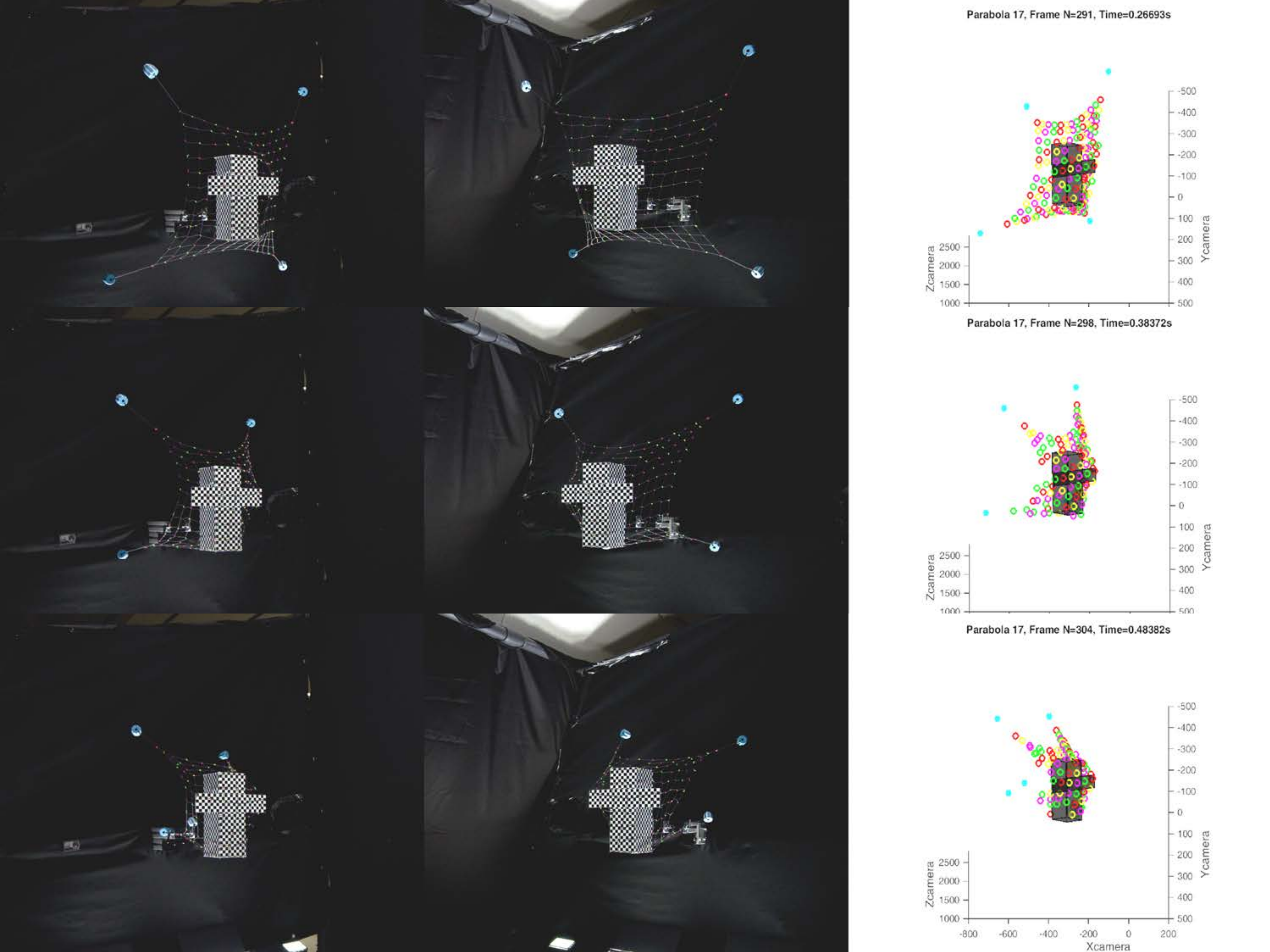
ESA's sponsored activity **PATENDER** [*Medina, 2015*]:
PoliMi in consortium with GMV Spain and Prodintec Spain

Experiment design:

- Nets shot at target mock-up
- Reconstruction of net 3D trajectory thought high resolution- high speed cameras
- Reconstruction process: based on net colour-coding, stereo-matching and knots tracking
- Target position and attitude reconstruction based on mock-up markers
- Simulator validation based on trajectory comparison

Novespace, Bordeaux, June 2015


Parabola 17, Frame N=281, Time=0.1001s
Parabola 17, Frame N=283, Time=0.13347s
Parabola 17, Frame N=285, Time=0.16683s
Xcamera
Ycamera
Zcamera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Zcamera
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Xcamera
-500
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-300
-200
-100
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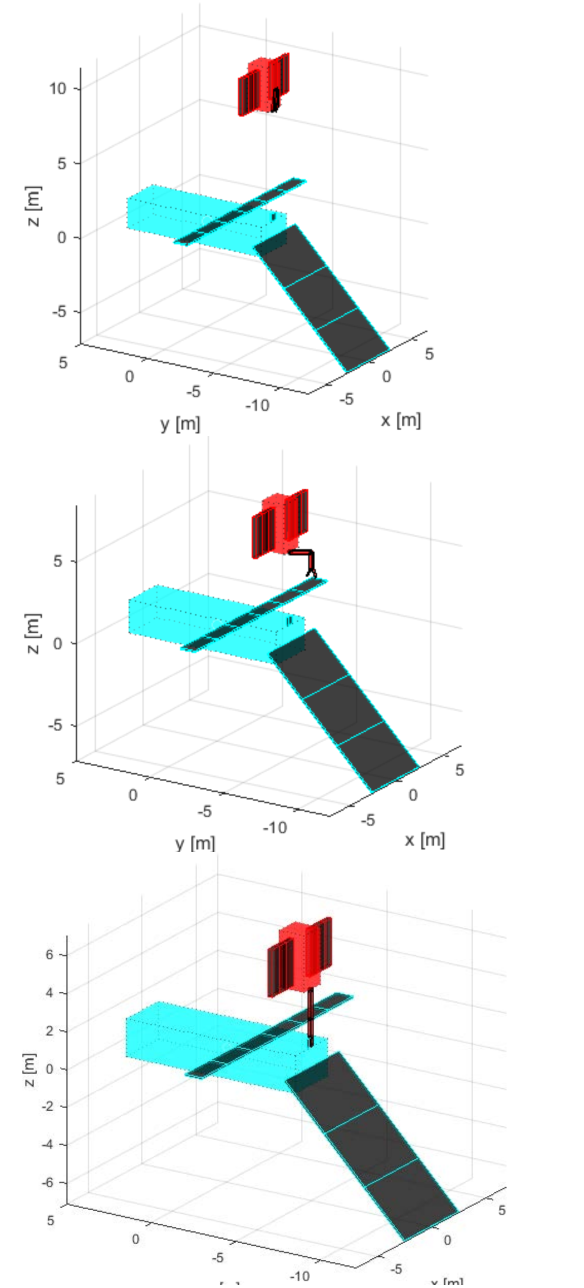
100
200
300
400
500
2500
2000
1500
1000
-800
-600
-400
-200
0
200

Robotic Arm Scenario

GNC

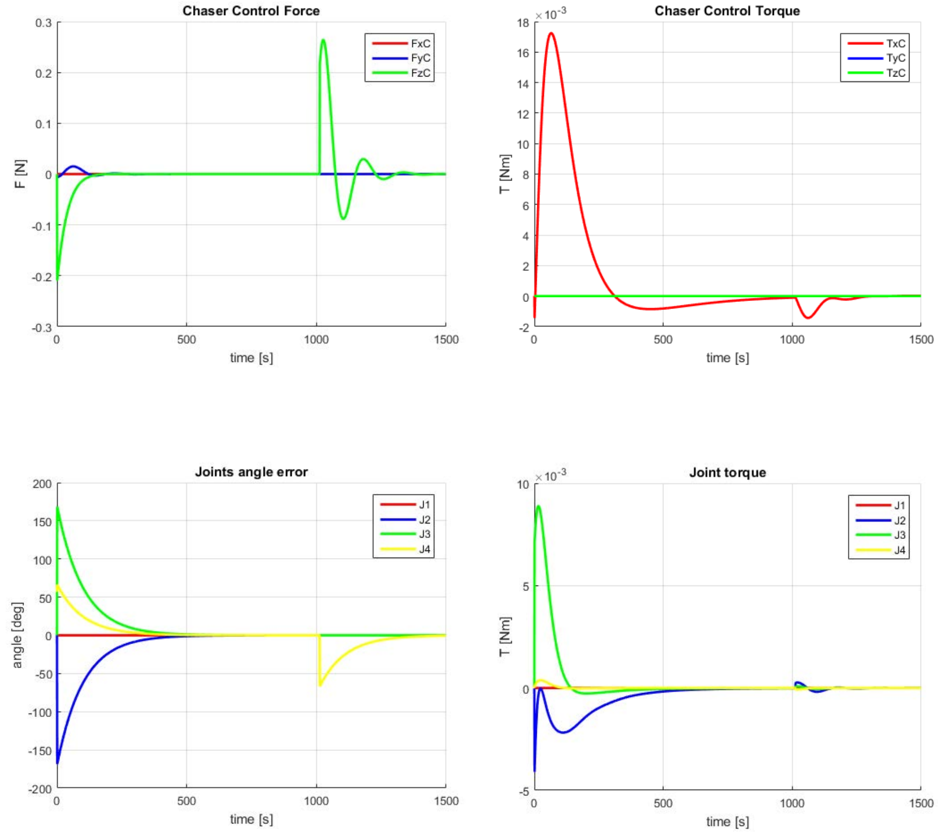
- Different guidance phases:
  - Motion synchronization at safe distance
  - **Final approach along H axis and arm deployment**
  - **Capture & rigidization**
  - De-tumbling and disposal
- **Coordinated control strategy** (decoupled):
  - Chaser:
    - LQR for relative position control
    - Eigenaxis attitude control
  - Arm:
    - Joints coordinates & Cartesian coordinates (IK)
- Noisy measurements + Kalman Filter

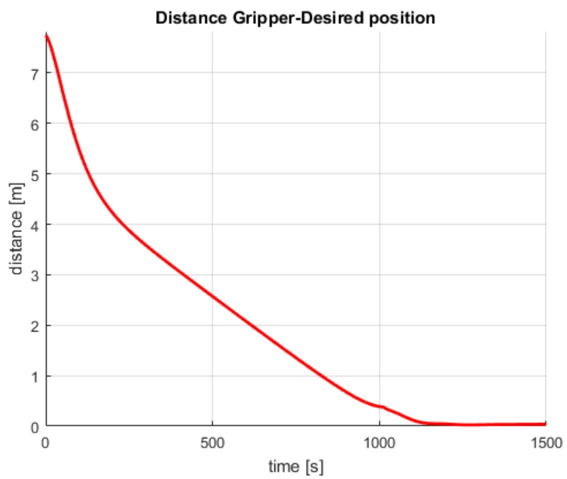


Robotic Arm Scenario

Chaser Mass [kg]	1450
Target	Envisat (simplified model)
Target angular velocity [deg/s]	3.5 H-axis
Arm Mass [kg]	30
Arm links [#]	2 + Gripper
Arm DOF [#]	4
Forward reach [m]	3.1
Control set-point rate [Hz]	10
Joints angular accuracy [deg]	0.3

Capture simulation results





Conclusions

- **Autonomous servicing/removal missions**:
    - complex, multidisciplinary and challenging task
    - capturing tumbling objects not equipped with dedicated docking ports
    - sophisticated technologies and reliable lightweight manipulators
- Developed **dynamics simulator** allowed
    - to assess the capture technique feasibility
    - **to drive system design**
    - **to support GNC design**
    - selected mathematical model ensures
        - fast and numerically stable simulations
        - flexibility in different scenarios analysis
    - **Experimental activities on-going to validate simulation models and test G&C**
- Throw-nets and towing-tethers VS. robotic manipulators
    - different scenarios analysed
    - preliminary G&C laws tested in simulation
        - Open loop preferred for tether
        - Closed loop preferred for arm

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