POLITECNICO MILANO 1863

DIPARTIMENTO DI SCIENZE E TECNOLOGIE AEROSPAZIALI

Cleaspace Industrial Days, May 23-27, 2016

ESTEC, the Netherlands

Politecnico di Milano activities to improve the Active Debris Removal technlogy readiness

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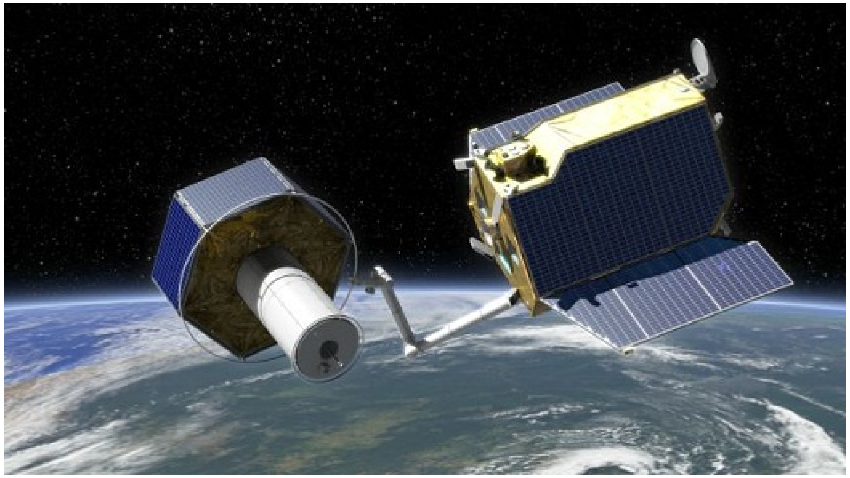
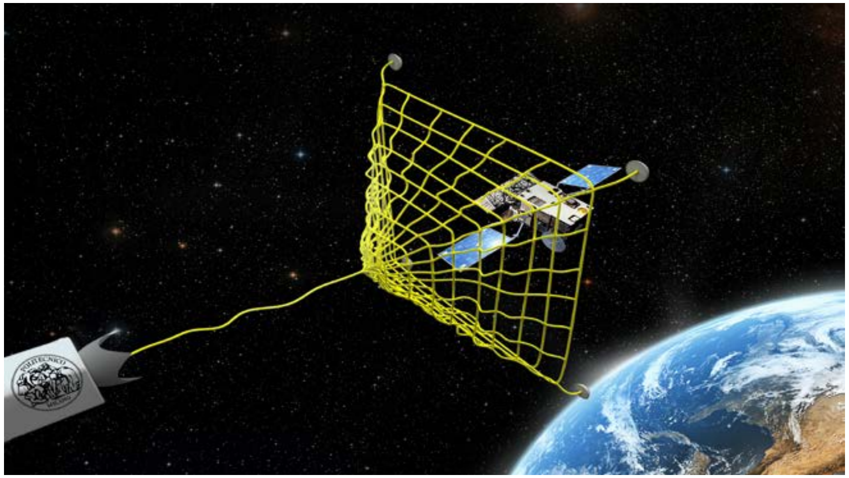
ADR Techniques – State of the Art

Rigid **VS.** ***Flexible***



DEOS: credits DLR



NEST: credits PoliMi

- Robotic arms & grippers
- **Establish rigid connection** – motion synchronization, closer approach
- **Pushing** action (in front of target)

- Nets, harpoons, tethered robot, sails
- **Establish flexible connections** – vibration damping and avoid instabilities
- **Pulling** action (behind target)

PoliMI past and current activities in ADR – Summary

Financed studies

Active Debris Removal Study
Responsible for assessment of tethered Net p\l feasibility-KT-ESA

ADR by AVUM adaptation
Responsible for tethered Net p\l sizing for AVUM- ELV-ESA

MUST study
Responsible for design, implementation and V&V of Multiple-body Dynamics Simulation tool - ESA

PATENDER-net dynamics validation in microgravity
Design and implementation of net dynamics simulator; design of the parabolic flight p\l; experiment running; post processing.GMV- ESA

e.Deorbit Phase A
Design of the tethered net p\l and operations; OHB- ESA

e.Deorbit Phase A CCN
Implementation of the tethered stack dynamics; TAS-F- ESA

VINAG
Assessment of the visual –GNSS data fusion for relative navigation TSD-ASI

closed
ongoing

Internal research

Uncooperative objects pose reconstruction
Visual based reconstruction of mechanical and geometrical target features

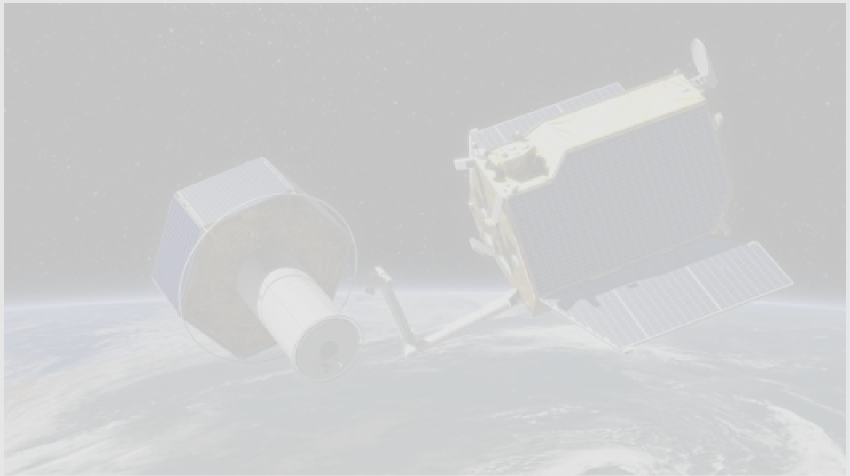
TETRIS
Phase A study on scaled IOD mission with nanosats for net based debris capture

Rigid connection multibody dynamics
Upgrade of MUST for robotic arm dynamics control during proximity, capture, disposal phases. On ground testing with HW in the loop.

SatLeash
Parabolic Flight experiment **for in house SW flexible connection dynamics and control validation**

ADR Techniques – Project Rationale

Rigid ***VS.*** ***Flexible***



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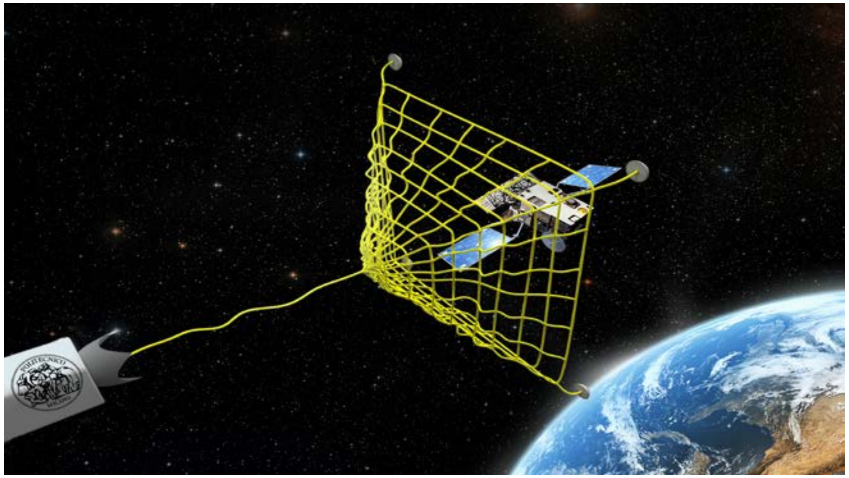


NEST: credits PoliMi

- Nets, harpoons, tethered robot, sails
- **Establish flexible connections** – vibration damping and avoid instabilities
- **Pulling** action (behind target)

To study tethered system dynamics,

no matter of the capture method

SatLeash – Towing A Satellite

Microgravity Experiment on Active Debris Removal Systems

for a Sustainable Access to Space

PoliTethers Team selected for **ESA's Education Fly Your Thesis! 2016**:

- Opportunity to **fly scientific experiment on tethered tug in microgravity conditions**
- **3-days parabolic flight campaign** onboard Novespace Airbus A310 Zero-G, **Autumn 2016**

fly your thesis!

PoliTethers Team:

Riccardo Benvenuto, PhD Candidate

Paolo Lunghi, PhD Candidate

Vincenzo Pesce, PhD Candidate

Andrea Bellanca, Master Student

Simone Rafano Carnà, Master Student

Endorsing Professor:

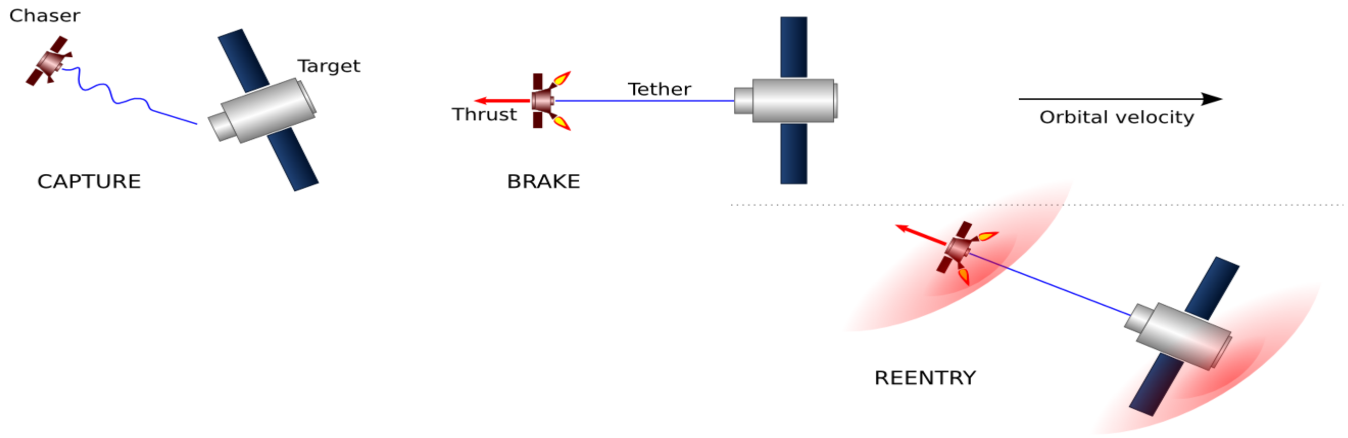
Michèle Lavagna

Outline

- **SatLeash Experiment**
  - Scientific background
  - Project goals
  - Scaled model vs. reference scenario
  - Tether Control
- **Microgravity and parabolic flights**
  - G-jitter analysis
- **Experimental set-up**
  - Configuration & Sensors
  - Procedures
- **Expected outcomes**

credits NoveSpace

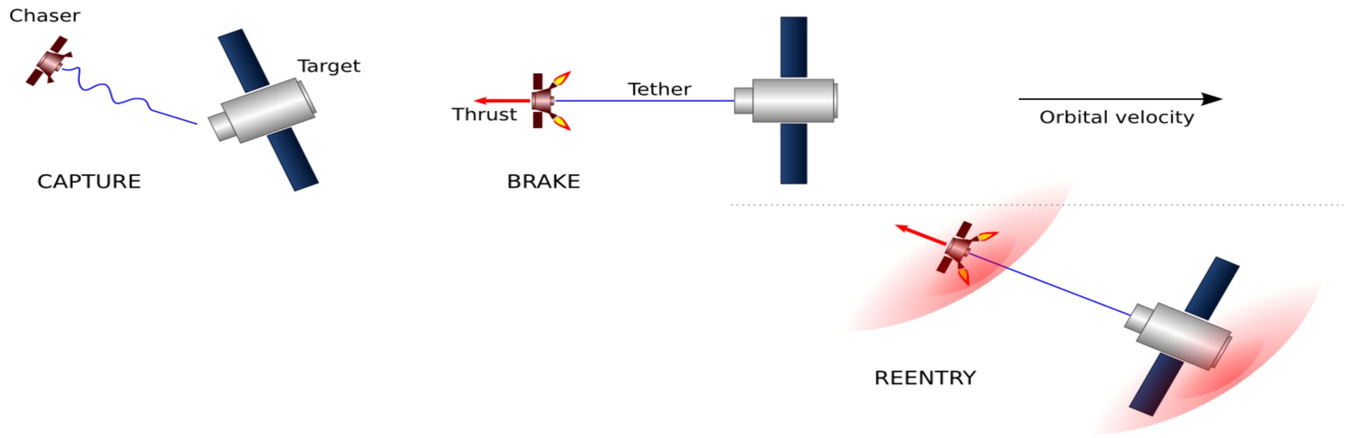
SatLeash Experiment – Project Background



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
- **Fast dynamics**
- Target mass > Chaser mass

SatLeash Experiment – Project Background



Research on tethered tugs needs:

- Understand and **model** the involved highly **non-linear phenomena**
- Implement **validated numerical simulators** to support system and GNC design
- Increase **Technology Readiness Level** (TRL) with tests in relevant environment

Tethered Tugs experiments rationale:

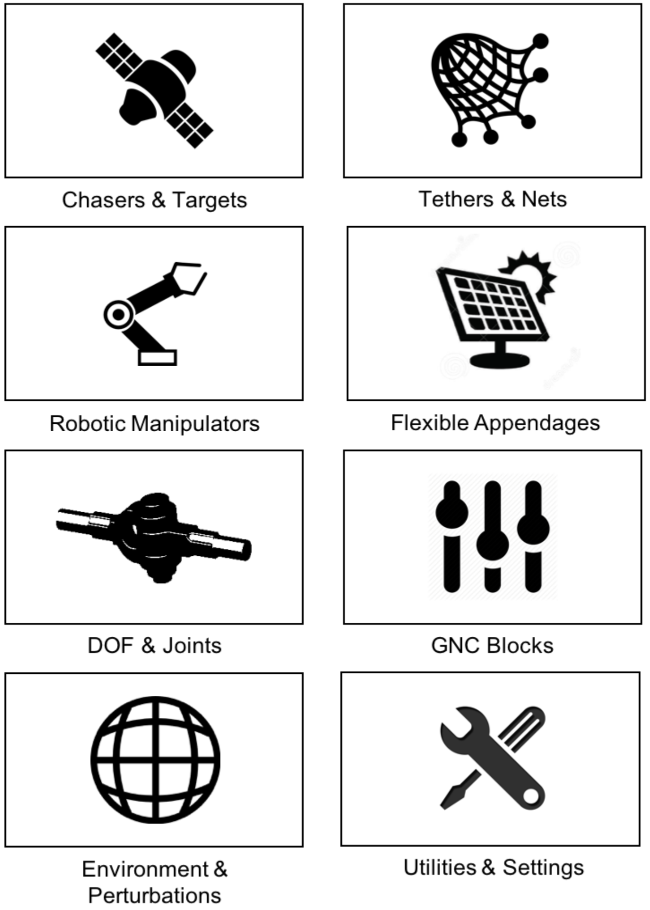
- Study the **overall system 3D dynamics** behaviour in **zero-g**
- Analyse bounce-back and whiplash effects

→ Parabolic flight facilities **suitable** for microgravity **time span and available test area**.

SatLeash Experiment – Project Background

PoliMi MULTIBODY SIMULATOR for Tethered Satellite Systems

- **Fast** simulation environment to **support GNC design**
  - **MUST toolbox core** developed under **ESA study**
- **User defined** scenario components
- Fully integrated in Matlab/Simulink
  - **Simulink libraries**
  - **SimMechanics**
- Modeled 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** (partially)



SatLeash Experiment – Project Background

TUG critical modes

- **Whiplash effects**
  - Leads to difficult control recovery
  - tether tensioning and stabilization needed
- **Bounce-Back effects**
  - post burn phase - slack tether
  - possible collisions due to residual tension
- **Tether entanglement and breakage**
  - slack tether avoidance needed
- **Atmospheric re-entry**
  - chaser control authority holds till a minimum altitude where drag on target prevails

Stack G&C

Closed loop:
Tension feedback to reduce bounce-back
- Stabilization + Bang-off + post-burn recovery

WAVE BASED control

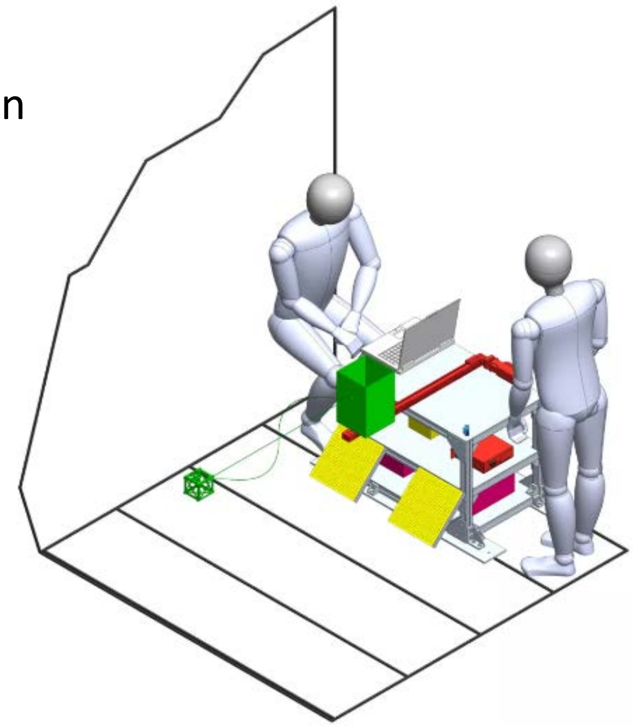
Open loop:
Feed-forward shaping of commanded thrust profile
- Input shaping
- Command smoothing/filtering

Closed loop attitude control

SatLeash Experiment - Goals

- **Objectives:**
  - **Study tether 3D dynamics** to validate flexible models
  - Study tether **effects on the end-body** (bounce-back, torques)
  - **Test control laws for flexible systems** and verify their effectiveness in stack stabilisation
  - **Increase the TRL** for a following on-orbit demonstration mission.

- **Experiment main blocks:**
  - **Tethered system scaled module**
  - Actuator to **simulate thrust profiles**
  - Stereo-vision + acceleration & tension sensors to **reconstruct dynamics**

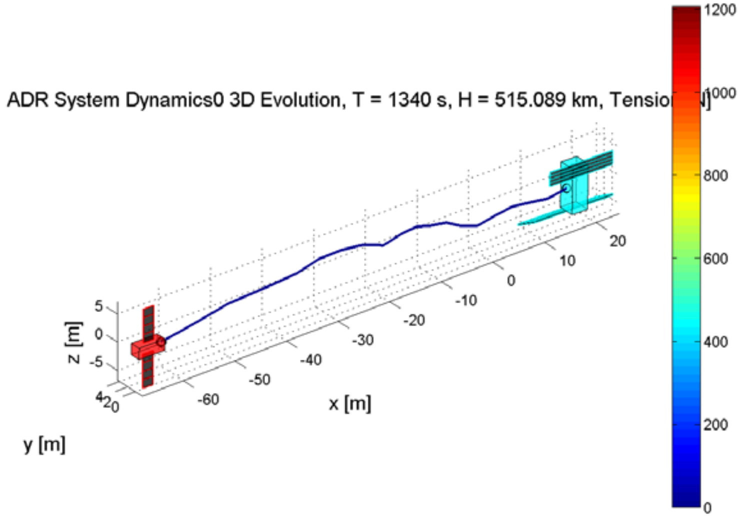


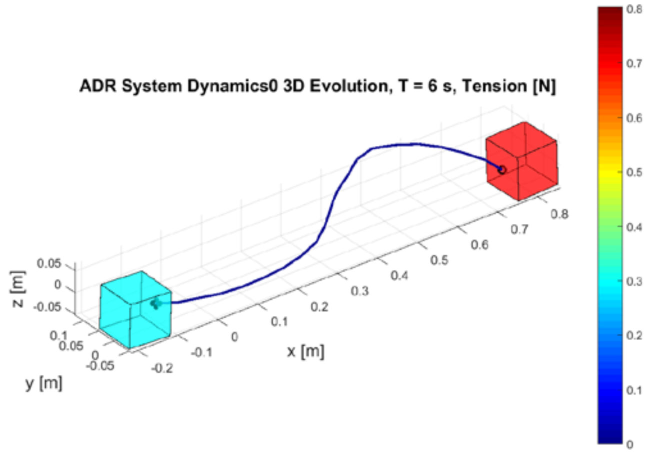
Envelope study of the SatLeash experiment setup.

Scaled Model vs. Reference Scenario

Dynamics Similitude

Reference Scenario **VS.** *Test Scenario*





Scaled model parameters obtained through:

- Buckingham Pi theorem (constant non-dimensional terms)
- **Dynamical similitude**
- Distorted geometrical similitude (diameter cannot be scaled as length)

$$S_F = \frac{S_M S_L}{S_T^2}$$

Scaled Model vs. Reference Scenario

Example of scaling results:

	Reference Scenario	Experimental Model	Scale
Diameter [mm]	3	1	3
Length [m]	500	1	500
Young's modulus [GPa]	120	1	120
Target Mass [Kg]	8000	1	8000

Tension [N]	540	0.5	1080
Stiffness [N/m]	1700	785	2.16
Stress [MPa]	76.4	0.637	120000
Strain [%]	0.0637	0.0637	**1**
Frequency [Hz]	0.0733	4.46	0.0164
Acceleration [m/s^2]	0.0675	**0.5**	0.1350
Time [s]	**183**	**3**	**60.86**
Delta-V [m/s]	**12.3**	**1.5**	**8.22**

SatLeash Experiment - Tether Control Strategy

- **Objectives:**
  - **Damp tether axial vibrations** during different phases from beginning to end of thrusting phase
  - **Damp tether oscillations** (whiplash effects, entanglement and breakage)
  - **Bounce Back effect** mitigation to avoid collisions

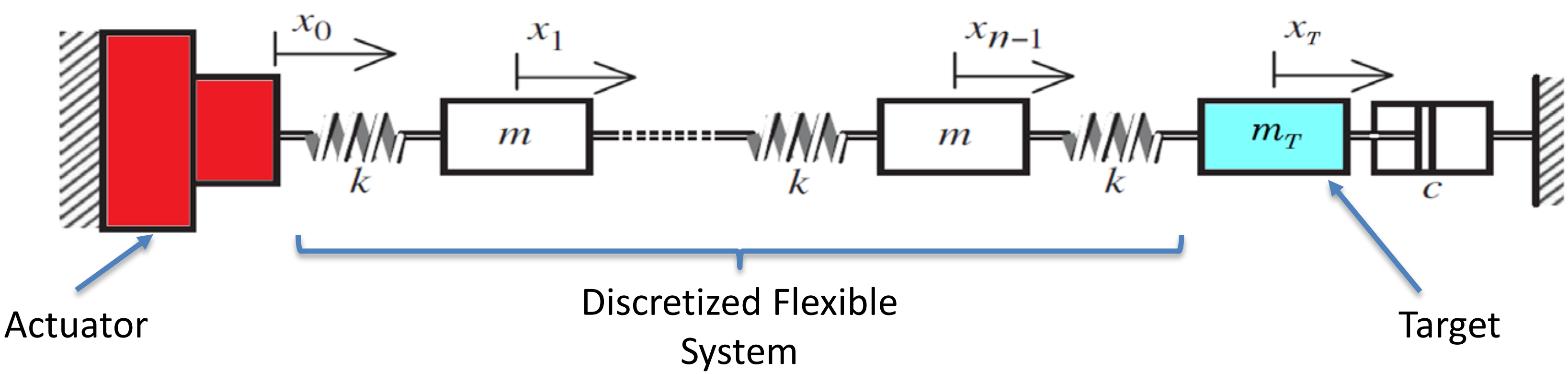
- **How:**
  - Thrust control
  - Smooth elimination of residual tension inside tether
  - Tether alignment to drive force vector direction
  - Robustness to off-nominal conditions
  - Robustness to external disturbances

WAVE-BASED CONTROL → *based on measuring and absorbing* ***mechanical waves*** *at interface*

SatLeash Experiment - Tether Control Strategy

Wave-Based Control

- Actuator behaves as an **ACTIVE viscous-damper** at the end of the tether
    - o through the WB controller action the system becomes constrained to an imaginary **skyhook** (same effect in orbital configuration)
    - o **Over-damped dashpot** to avoid tether collapsing during release phase: demonstrated to be always stable if over-damped
- **Tension Feedback** needed



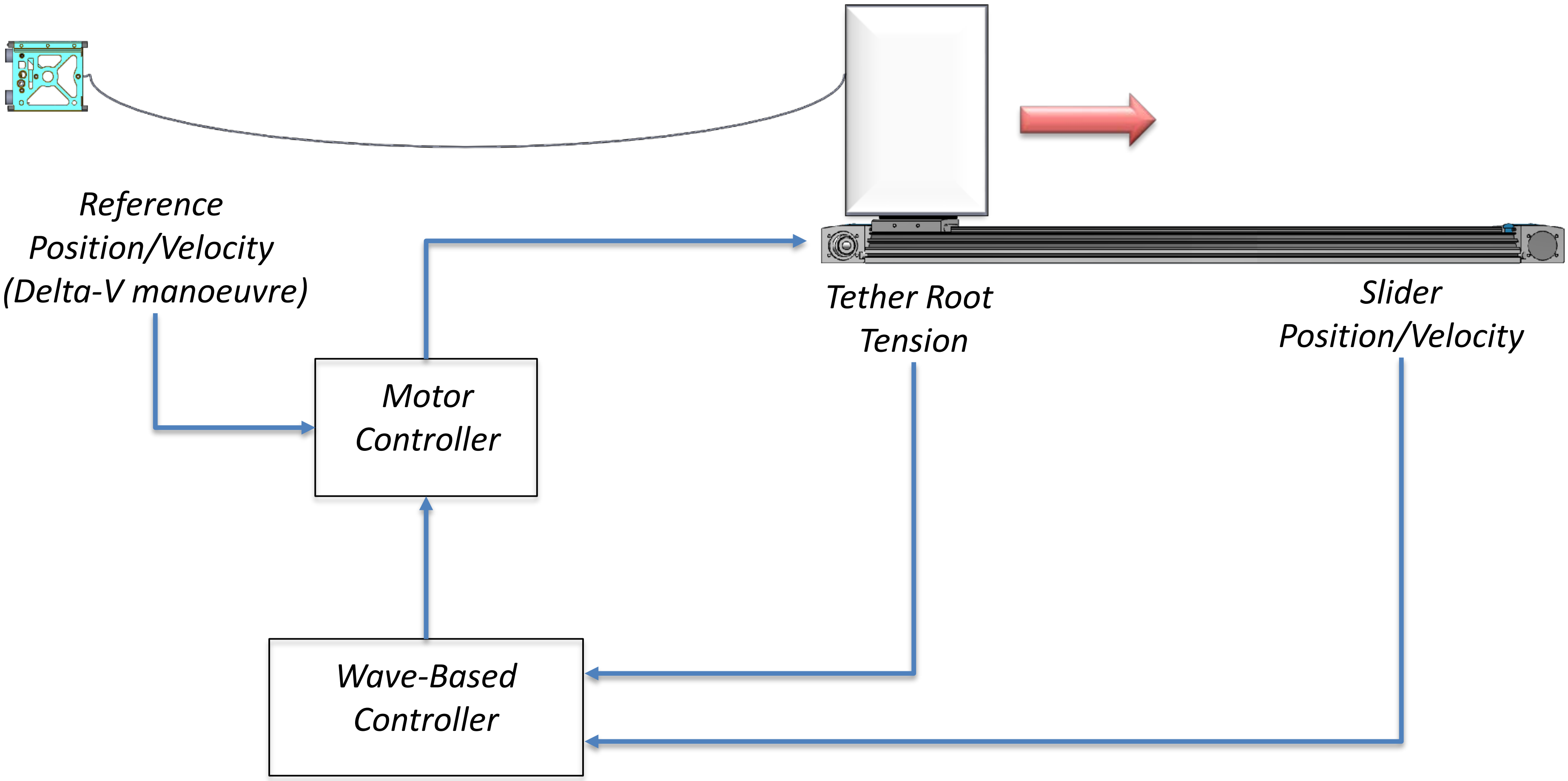
Control Law

$$x_o(t) = a_o(t) + b_o(t)$$

$a_o(t)$: *Launch Wave*

$b_o(t)$: *Returning Wave* ← *Absorbed* **DAMPING EFFECT**

Tether Control Strategy - Experiment Architecture

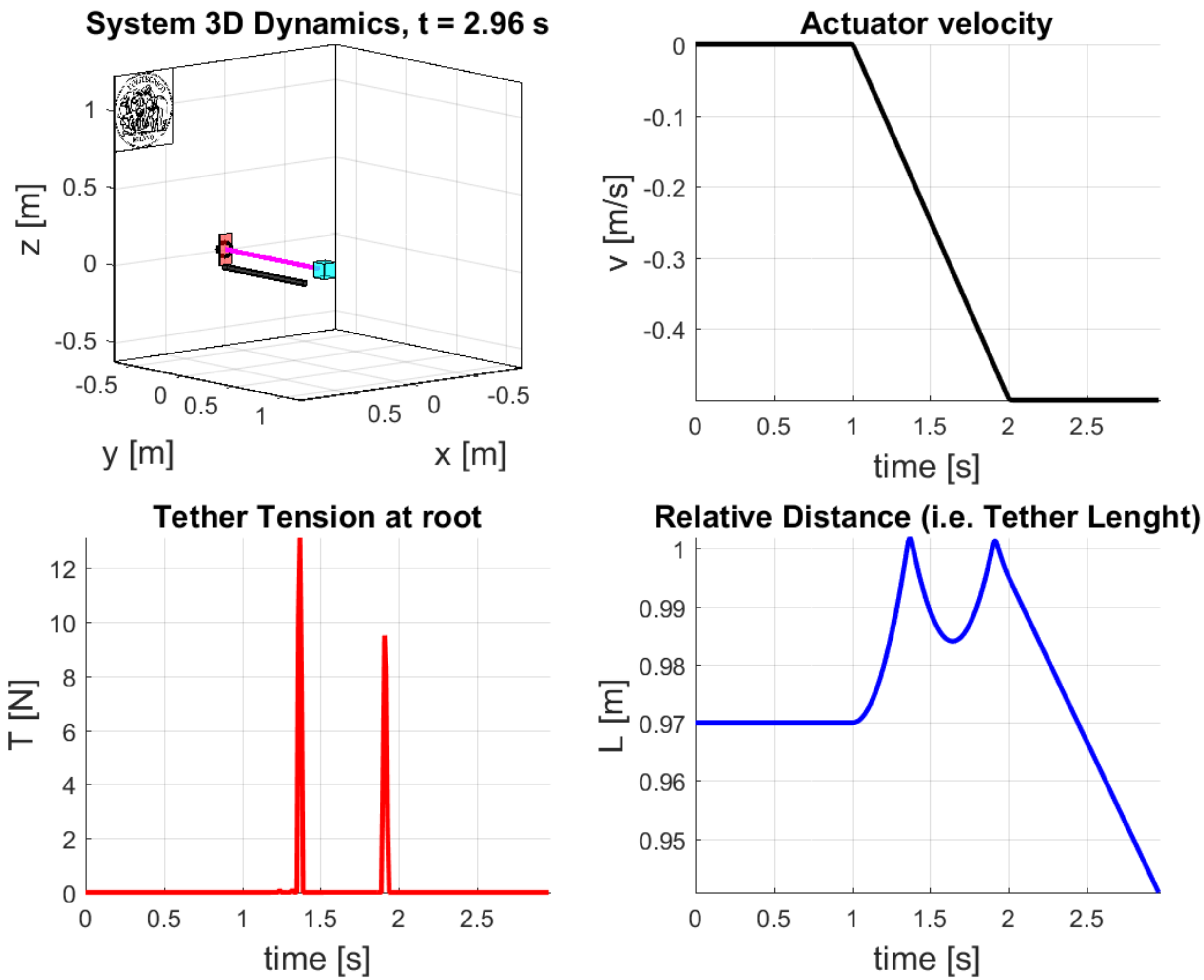


Tether Control Strategy– Simulation output

WBC OFF

Tether Control Strategy– Simulation output

WBC OFF

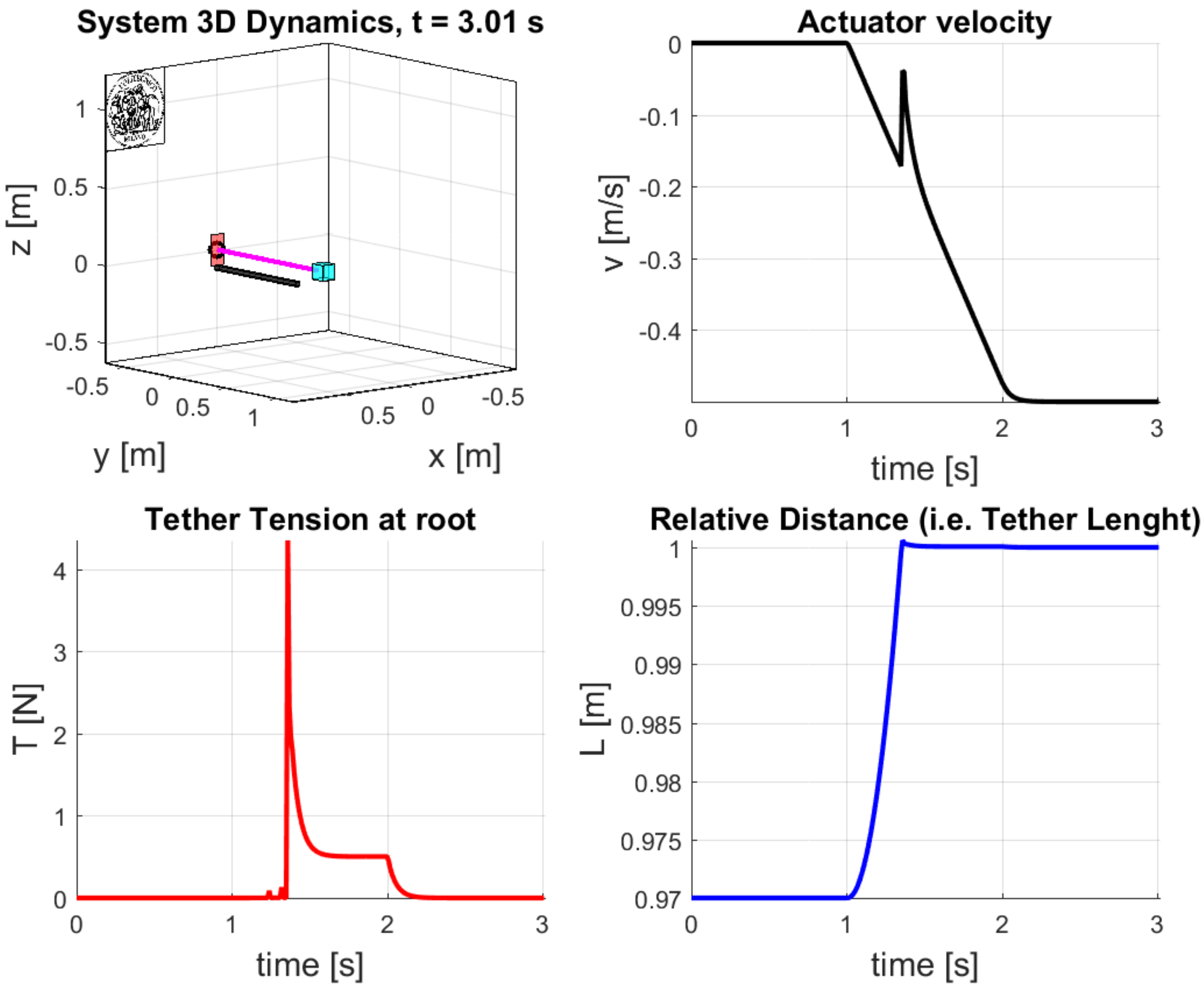


Tether Control Strategy– Simulation output

WBC ON – DISTURBANCES OFF (to show control effect)

Tether Control Strategy– Simulation output

WBC ON – DISTURBANCES OFF (to show control effect)



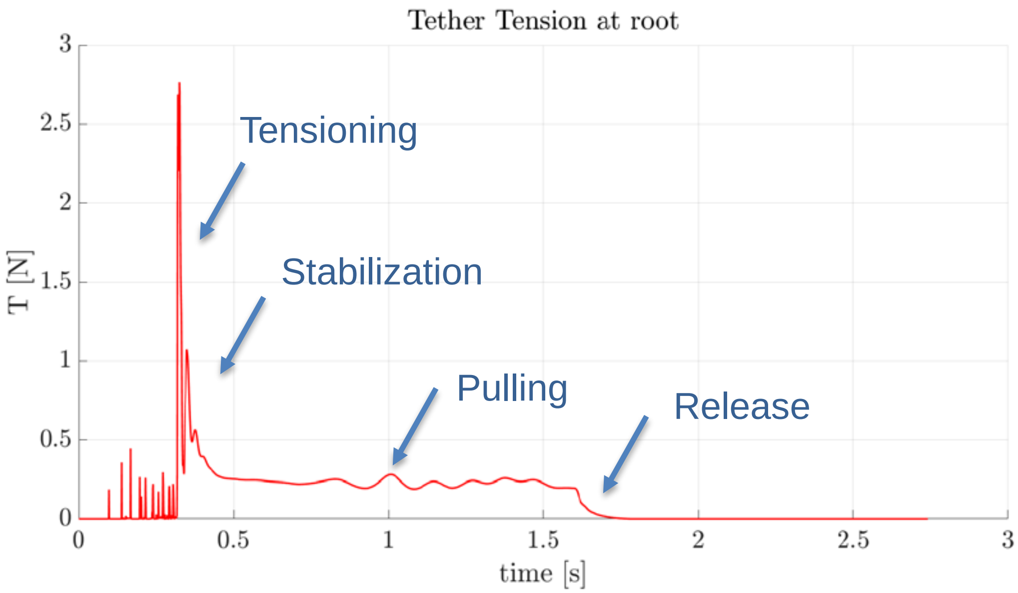
Tether Control Strategy – Simulation Output

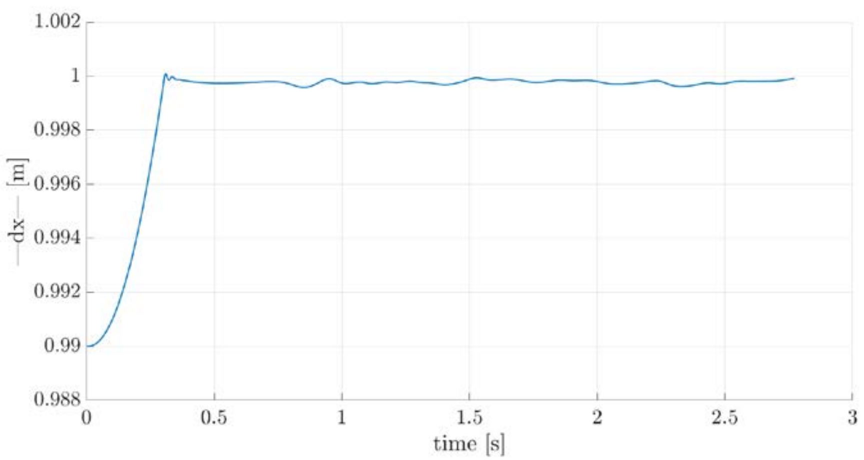
Simulated manoeuvre

- G-jitter included (results still valid)
- Initial tensioning and stabilization
- Pulling phase: constant tension until Delta-V
- Release phase: thrust OFF

Remarks on results

- Bounce back effects strongly mitigated
- Robust to uncertainties and disturbances





Tether length at nominal condition at the end of transient response

Tether Control Strategy– Simulation output

DISTURBANCES INCLUDED - Target Deviation caused by G-jitter – Results NOT disrupted

Microgravity and parabolic flight

Relevance for testing in microgravity

- Gravity strongly affects tethers dynamics

→ **Investigation of some critical phenomena only possible in microgravity**

- full **3D breadboard in microgravity required** for **bounce-back** analysis
- **Tension laws** tuned on ground may be different in zero-g
- **synthetic braids behavior assessment** for orbital applications

→ **Assessment of damping characteristics**

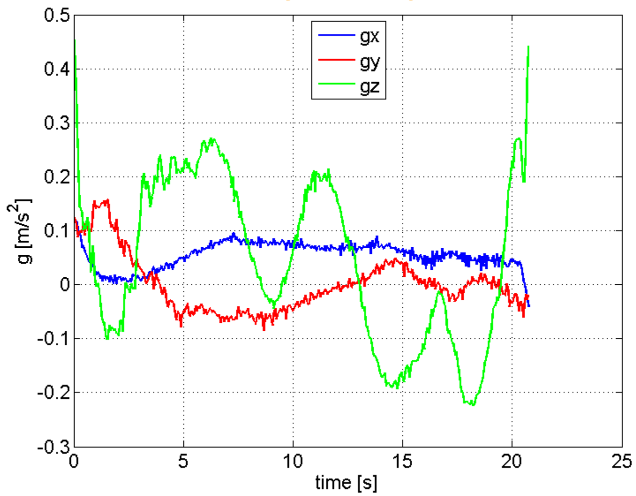
A310 ZERO-G flight suitability

- **Appropriate microgravity duration**: about **20 seconds** meets time-scale requirements
- **Appropriate available test area:** 2 x 2 x 1.9 m box meets length-scale requirements
- Possibility of **repetitions** for:
  - Statistical validation
  - **Test different** initial **conditions** and **parameters**
- Possibility to **act directly** on the experiment

Microgravity and parabolic flight

G-jitter analysis - Model Identification

Time history example case



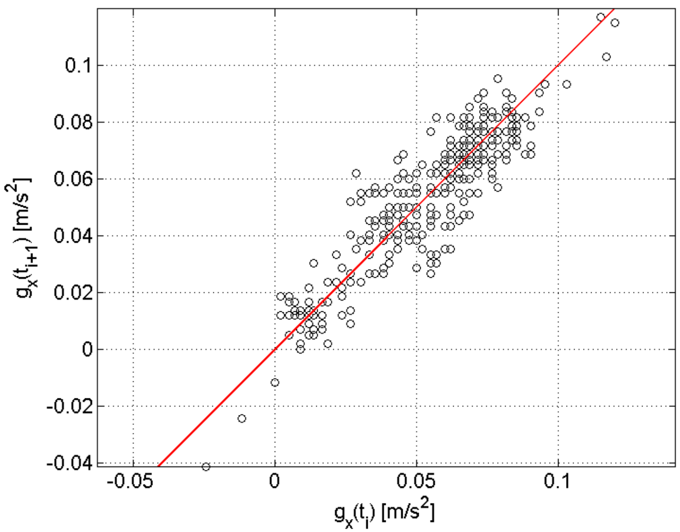
G-jitter time history:

- **Fixed** time step
- **Continuous random** variation
- **Normal distribution** of variations

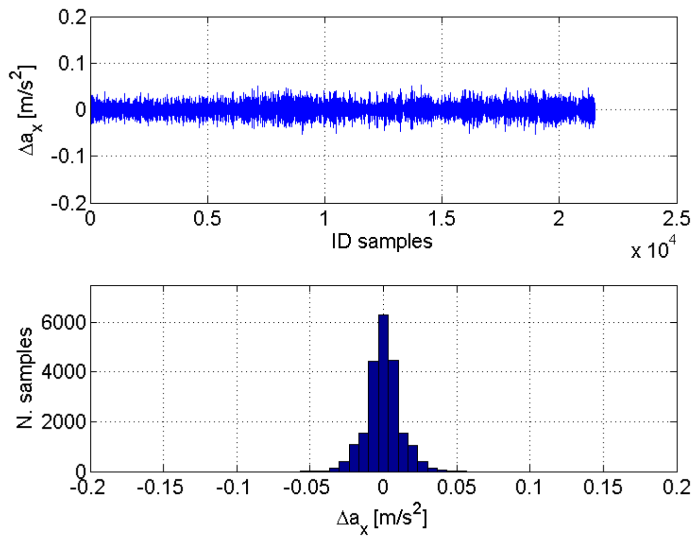
Null-mean **Random Walk** model:

$$g_{i+1} = g_i + \Delta g$$

Current time vs next time value



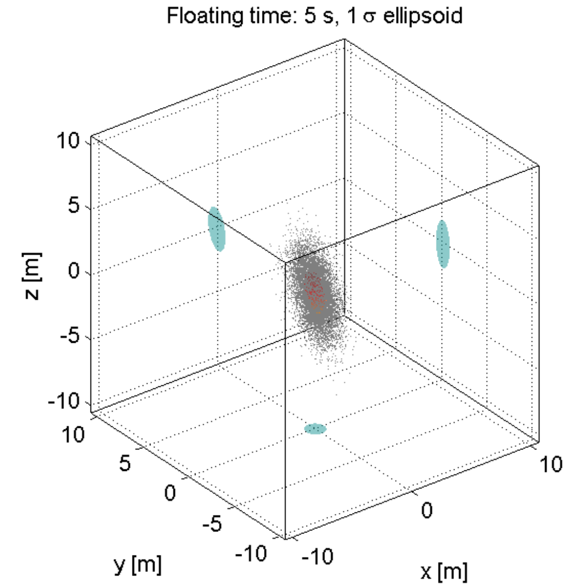
Δg Histogram (g_x all data)



Microgravity and parabolic flight - G-jitter analysis

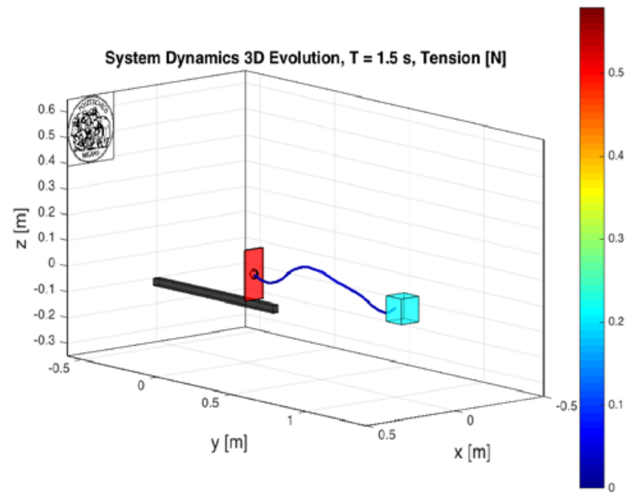
Monte Carlo Simulations

- **10000** samples
- Centrifugal and Coriolis components included
- Consider separately the effects due to g-jitter and to experiment position in aircraft
- **Impact over the experiment design:** size, length, floating module position, orientation/position of experiment inside aircraft



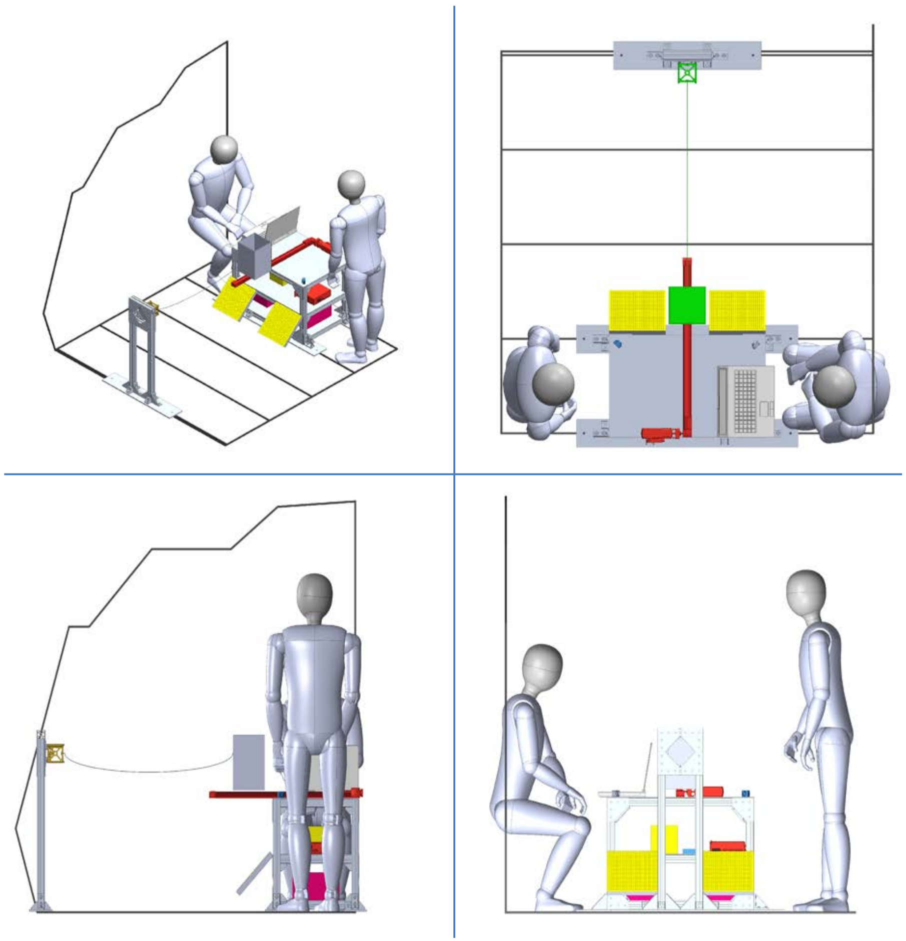
Control Simulations

- Acceleration profiles inserted
- **Tuning control parameters** and manoeuvre parameters to minimize disturbances effects



Experiment Set-Up – Configuration

- **Single 1U CubeSat floating module (representative for the target)**
- **Linear actuator representative for the chaser motion**



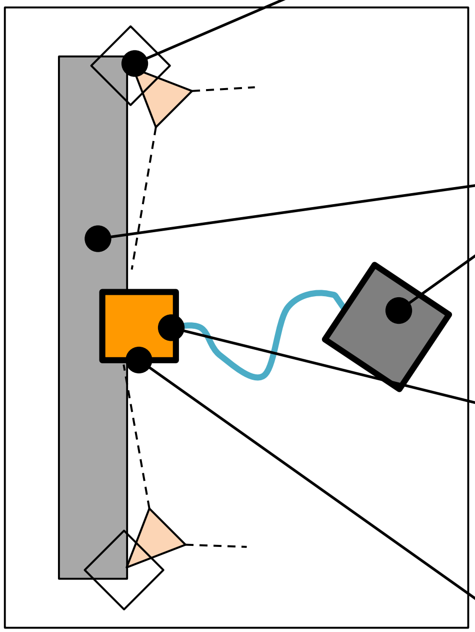
Main components & characteristics:

- Main rack 0.8x0.6x0.6 meters holding:
  - **stereo-camera** system
  - **illumination** system
  - Laptop/**acquisition** board
  - electronic box and IMU
  - storage boxes for spare parts
  - **linear actuator**

- Secondary supporting structure holding:
  - CubeSat-Tether floating system

- **Tether axis parallel to the pitch axis** to reduce differential perturbations

Experiment Set-Up – Sensors

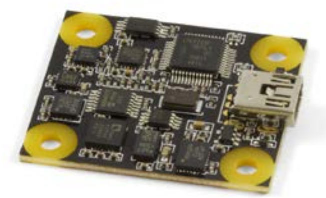


Cameras

3D reconstruct by stereo vision

IMUs

Acceleration and angular velocity on cube and rack

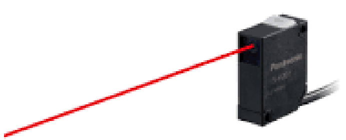


Load Cell

Tether tension

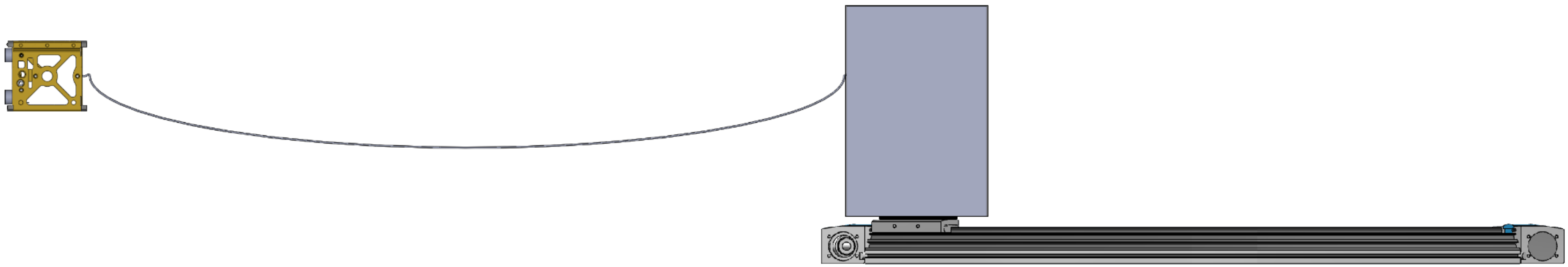
Slider Position/Velocity

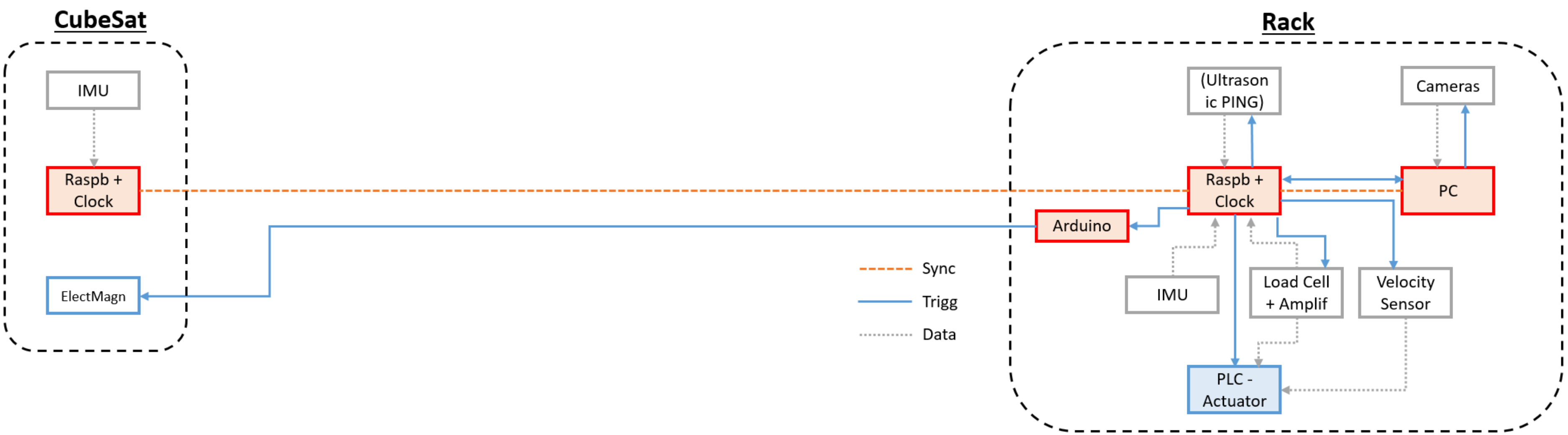
Laser sensor



All sensors to be synchronized by Arduino-like board

Experiment Set-Up - Electronics Schematic





Experimental procedures

Acquisition

- **Free floating body** connected by **tether** is released in controlled conditions in microgravity environment
- Sensors provide measures of **position**, **acceleration** and **tether tension**

Dynamic Reconstruction

- Recorded measures are exploited to **reconstruct the dynamics** and the evolution of the floating system

Initial Conditions Extraction

- Dynamic reconstruction provides **initial conditions** for the PoliMi DAER numerical simulator under validation

Numerical Simulations

- Numerical simulations are carried out with the **same set of measured initial conditions**

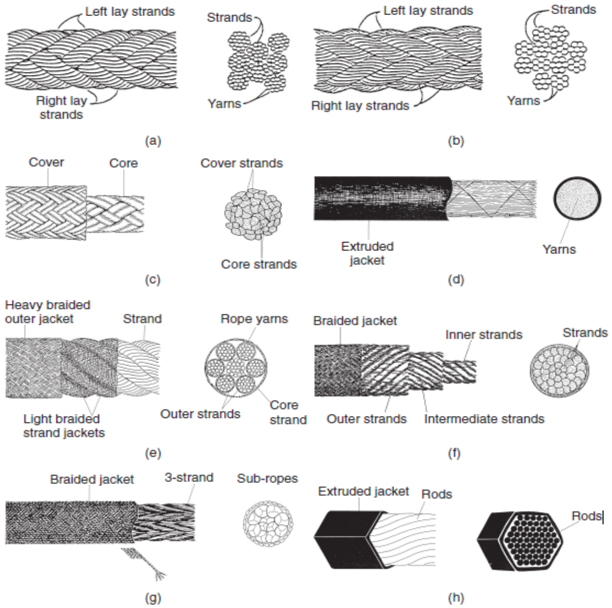
Comparison of Results and SW validation

Experimental procedures

material characterization

To fully **characterize tethers mechanical properties**, including damping, tensile tests and dynamical-mechanical tests (**DMA**) on ground, prior to flight

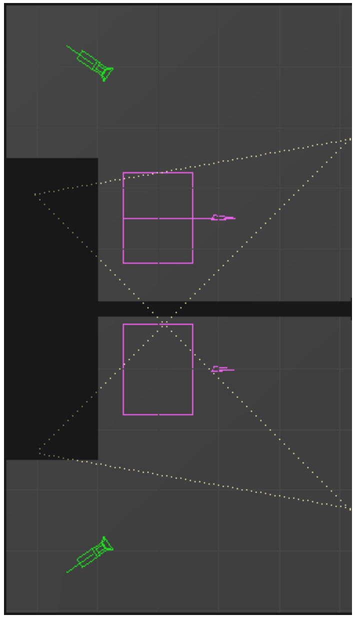
- **Tests allow reducing the number of uncertain parameters** in the flexible dynamics model validation process
- Final properties dependent on the tether configuration and manufacturing



Breaking stress [GPa]	1.626
Breaking strain [%]	6.43
Axial stiffness per unit length [N]	$0.63 \cdot 10^{3}$
Torsional stiffness per unit length [Nm^2]	$2.94 \cdot 10^{-6}$
Bending stiffness per unit length [Nm^2]	$1.34 \cdot 10^{-6}$
Axial damping ratio [-]	0.106
Torsional damping ratio [-]	0.079
Bending damping ratio [-]	0.014

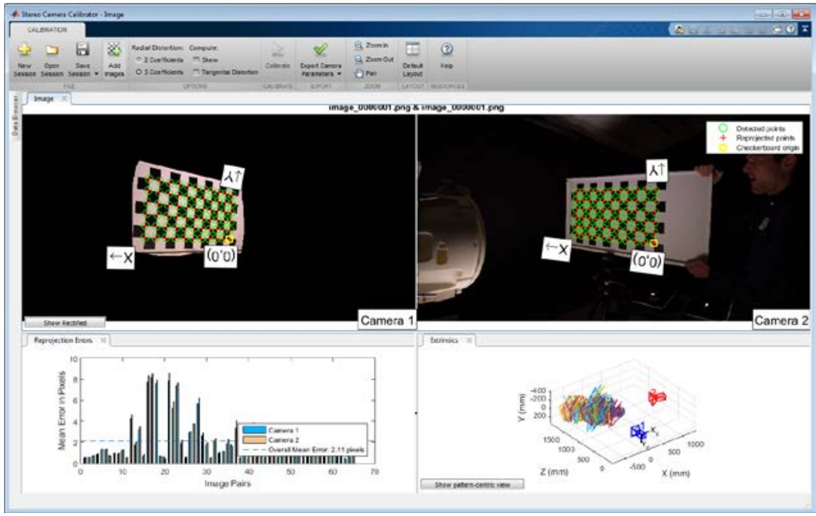
Experimental procedures

3D Trajectory Reconstruction



1. Design of
    - Cameras position/orientation and Field of views (focal length vs focus/depth of field)
    - Cameras settings (frame rate vs resolution)
    - In-flight calibration procedure

2. 3D reconstruction based on:
    - **Coloured markers** on tether
    - **Visual markers** on target body to reconstruct position and attitude and combine with IMU data



3. **Reconstruction SW**:
    - In-house developed tool exploiting Matlab toolbox
    - Developed in the framework of ESA activity PATENDER

Expected Outcomes

Test Procedures:

- **10 tests** for each configuration (same settings)
- During each flight: **3 different tests**, each **repeated 10 times**
- **9 different configurations** tested in the 3 days campaign

3D Reconstruction

Flexible model validation

Numerical simulator updating

Test & Validation of WB control techniques

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