Clean Space Industrial day

24-26 October, ESA-ESTEC

Tethered-tugs dynamics and control verification and models validation by 0g experiments on parabolic flights

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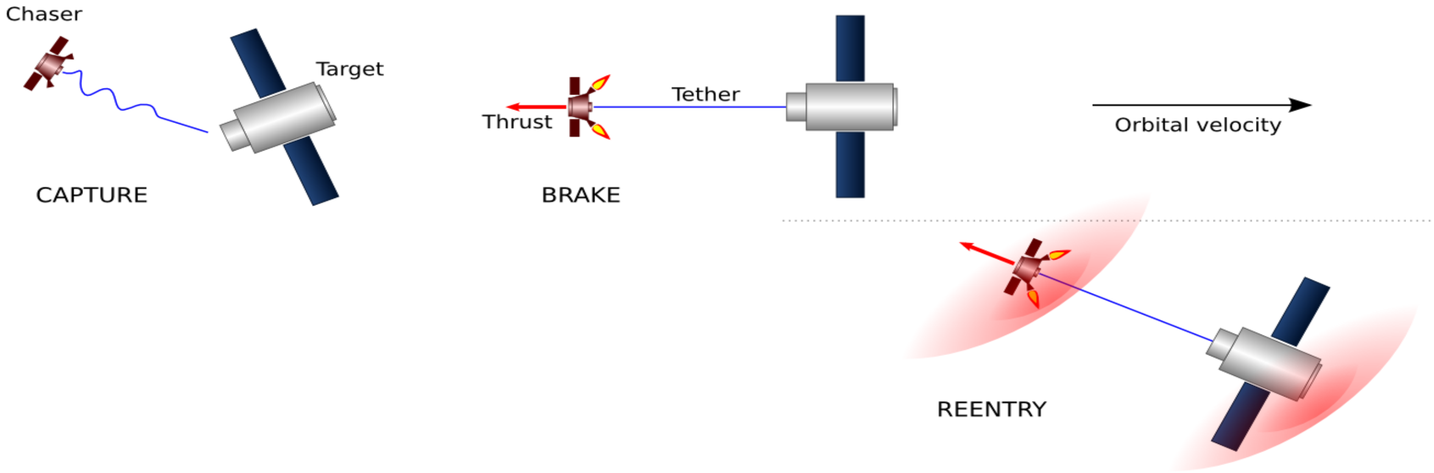
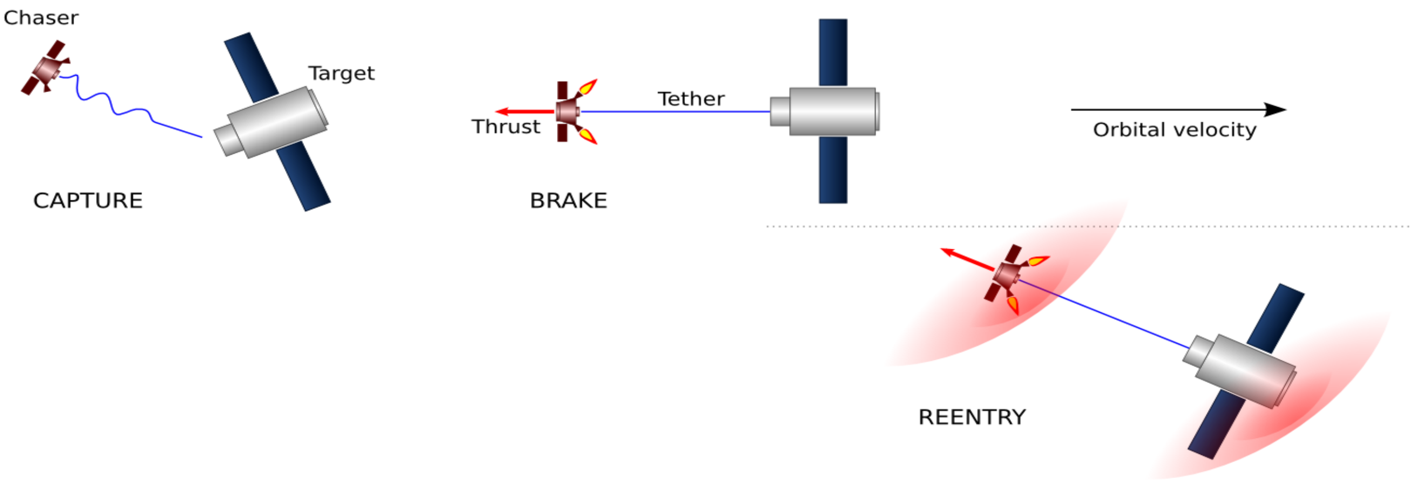
Introduction – Tethered ADR



- <u>Tethered Tugs</u> related **studies focus** on:
  - Understanding and **modelling** the involved highly **non-linear phenomena**
  - Implement **validated numerical simulators** to support system and GNC design
  - Increase **Technology Readiness Level** (TRL) with <u>tests in relevant environment</u>
- <u>Tethered Tugs</u> need **tests and simulations**:
  - Tethered system 3D dynamics **behaviour in zero-g**
  - Active **Control** for Tethered mated system

Introduction – Tethered ADR



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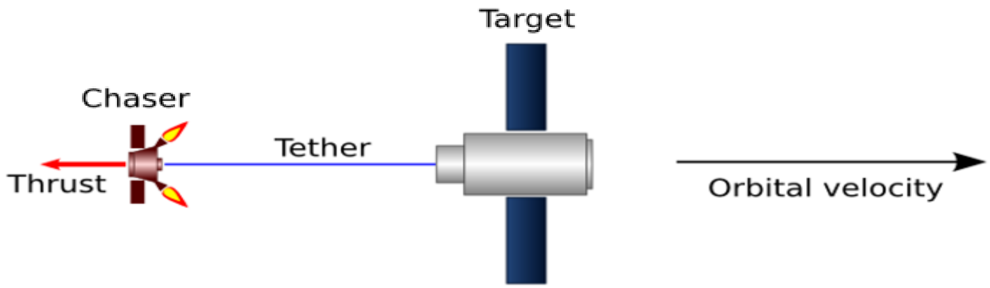
- Tethered Tugs need **TESTS and SIMULATIONS**
  - Tethered system 3D dynamics behaviour in zero-g
  - **Active Control for Tethered Mated Systems**

Outline

- **The Problem**
- **The adopted approach**
- **The Numerical Model**
  - *Flexible Model*
  - *Control Formulation*
- **The Experiment description**
  - *Architecture*
  - *Control Implementation*
- **Experimental Results**
  - *Data Reconstruction*
- **Comparison Numerical/Experimental**
- **Conclusions**

Open Issues in Tethered ADR



Pulling

Whiplash Effects

- Bouncing oscillation
- Uncertainties on initial slack
- Difficult control recovery

Stabilization Phase

Post burn

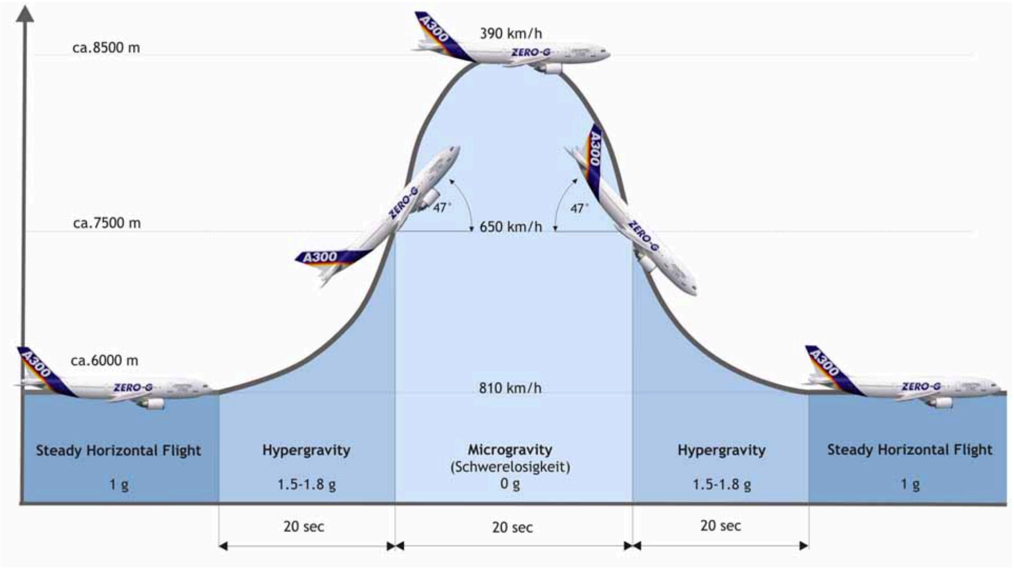
Bounce Back Effects

- Uncontrolled Elastic Recovery
- Uncontrolled Tether collapsing
- Risk of Collisions

Release Phase

Adopted Approach – Framework

Microgravity Experiment on Tethered System for Active Debris Removal Missions

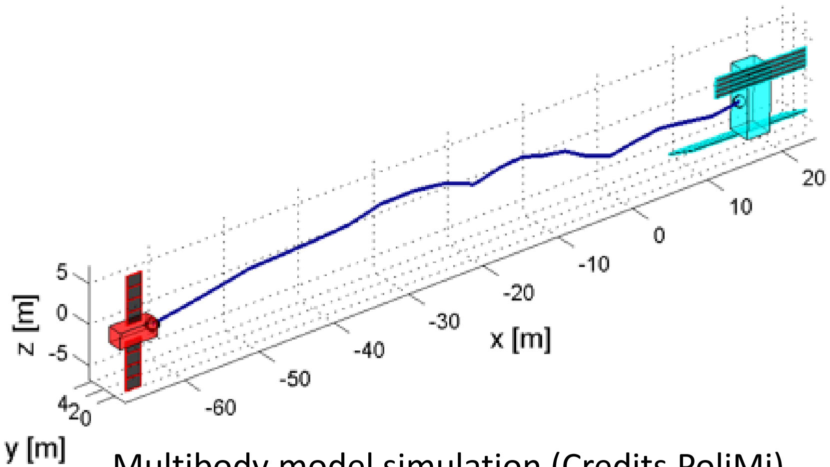


SatLeash Experiment selected for **ESA's Education Fly Your Thesis! 2016**:

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

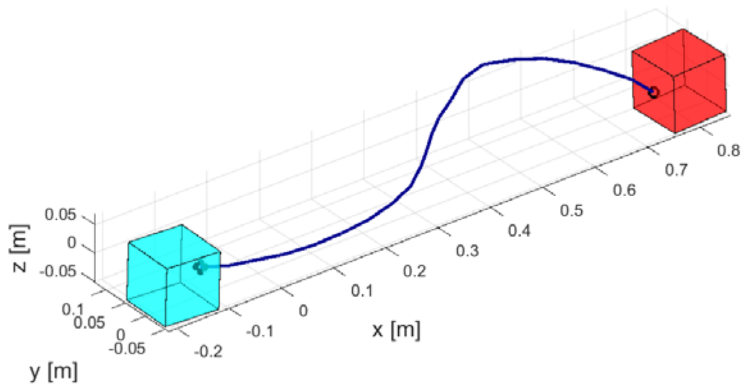
Adopted Approach – Scenario

Reference Scenario



Multibody model simulation (Credits PoliMi)

Test Scenario



Scaled simulation

	Reference Scenario	Test Scenario
Diameter (m)	1e-2	1e-3
Length (m)	**100**	**1**
Target Mass (Kg)	**7000**	**1.5**
Tension (N)	150	0.75
Acceleration (m/s^2)	2.1e-2	0.5
Time Manoeuvre (s)	**145**	**3**

Scaled Model*

Full dynamical similitude

**Parabolic flight experiment to validate tethered-tugs dynamics and control for reliable space transportation applications*, 67th International Astronautical Congress, Guadalajara, Mexico.

Study rationale

Acquisition

- **Experimental tests** reproducing tethered system scaled dynamics in controlled conditions in **microgravity** environment
- **Chaser state, target state** and **tether tension** monitored through sensors

Dynamic Reconstruction

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

Initial Conditions Extraction

- Dynamic reconstruction provides **initial conditions** for the numerical simulations

Numerical Simulations

- Numerical simulations are initialized coherently with **measured initial conditions**

Verification & Validation

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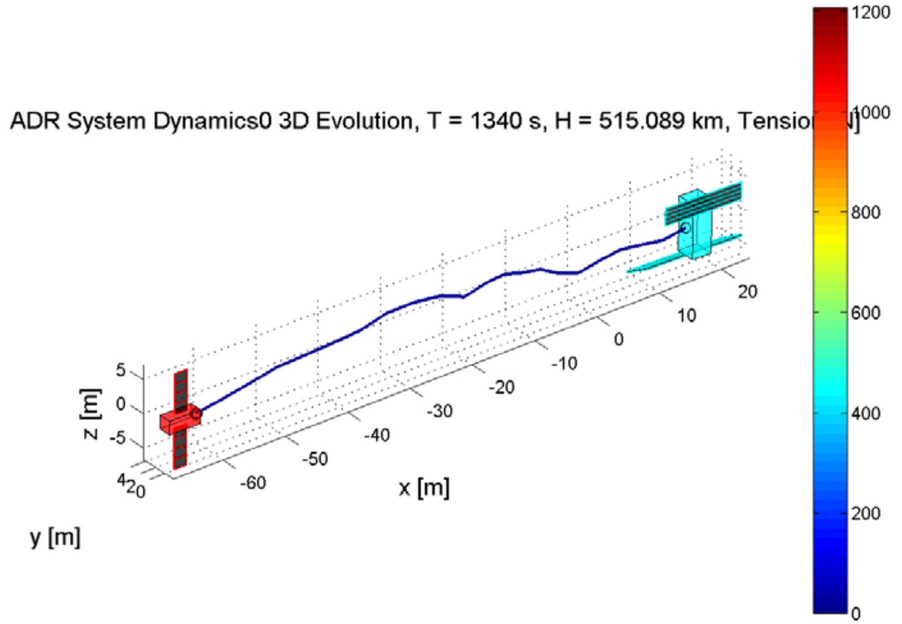
Numerical Model – Flexible elements

MUST:

MUltiple-body dynamics Simulation Tool for active satellite removal system

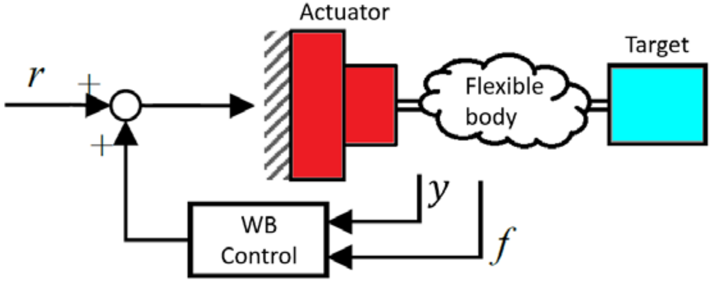
(PoliMi-ESA Study 2015)



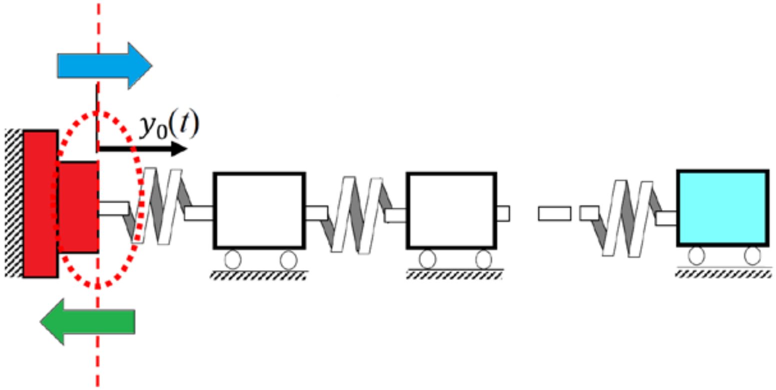
- Numerical simulator developed at Politecnico di Milano –DAER
- Last release in 2015
- Suitable for full scale tethered systems simulations and analyses
- Adopted to reproduce tethered mated system dynamics

Numerical Model – Control strategy

- **Wave-Based Technique (**O'Connor*):
  - Control of complex system in a simple way
  - The **interface** is the key
    - Understand the interface
    - Measure the interface features
    - Manage the interface
  - **Wave concept** applicable for all flexible systems



- **Waves Concepts:**
  - When actuator moves, it launches a wave
  - The wave passes through the flexible body
  - Wave reaches target
  - Returning wave moves toward actuator



Actuator damps the returned wave

"Debris de-tumbling and de-orbiting by elastic tether and wave-based control," in Proceedings of the 6th International Conference on Astrodynamics Tools and Techniques (ICATT), 2016.

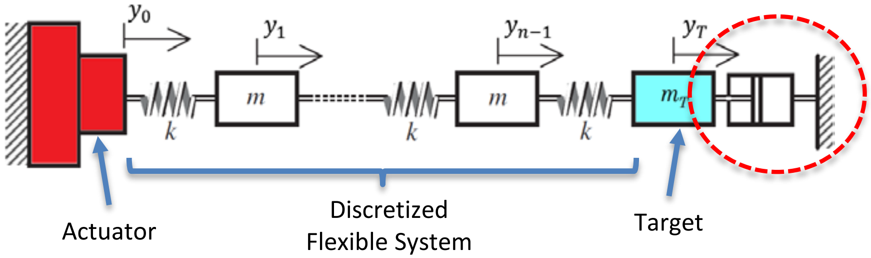
Numerical Model – Wave Based Control

Actuator behaves as **ACTIVE viscous-damper** at the end of the tether

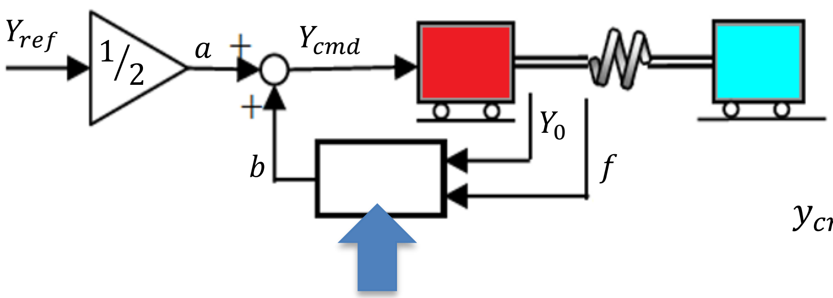
- the system becomes constrained to an imaginary **skyhook** which behaves like a **over-damped dashpot** to avoid tether collapsing during release phase

Inputs needed:

- **Tension Feedback**
- **Actuator Position/Velocity Feedback**



Control Scheme



$$\frac{1}{2}\left(y_0(t) - \frac{1}{\sqrt{k_t m_T}}\int f(t)\,dt\right)$$

$$y_{cmd}(t) = \frac{1}{2}y_{ref}(t) + b(t) = \frac{1}{2}y_{ref}(t) + \frac{1}{2}\left(y_0(t) - \frac{1}{Z}\int f(t)\,dt\right)$$

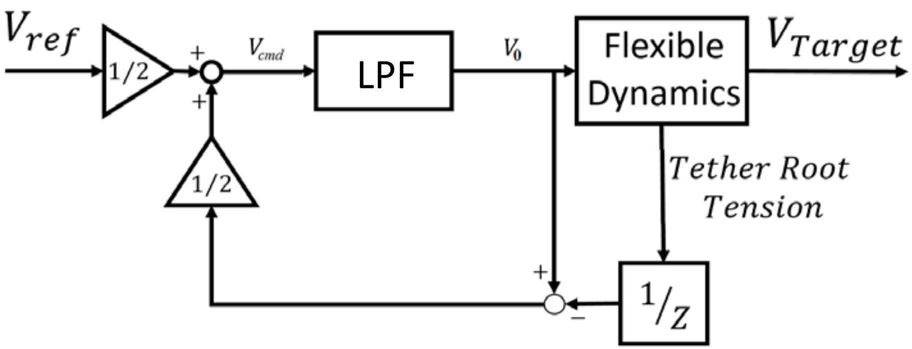
Controlled System damping ratio

$$\boxed{\xi_{WBC} = \frac{\sqrt{k_t m_T}}{2Z} \geq 1}$$

Z: CONTROL PARAMETER

Numerical Model – Wave Based Control

- **Velocity** Control Scheme:

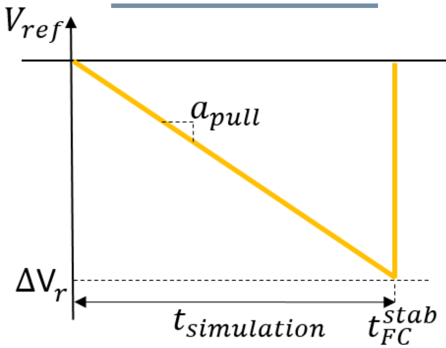


- **Control Law:**

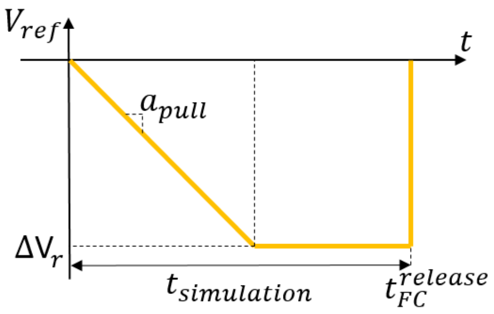
$$V_{cmd}(t) = \frac{1}{2} V_{ref}(t) + \frac{1}{2}\left(V_0(t) - \frac{T(t)}{Z}\right)$$

- **References:**

Stabilization



Release



Numerical Model – Wave Based Control

WBC OFF – DISTURBANCES ON

Numerical Model – Wave Based Control

WBC ON – DISTURBANCES ON

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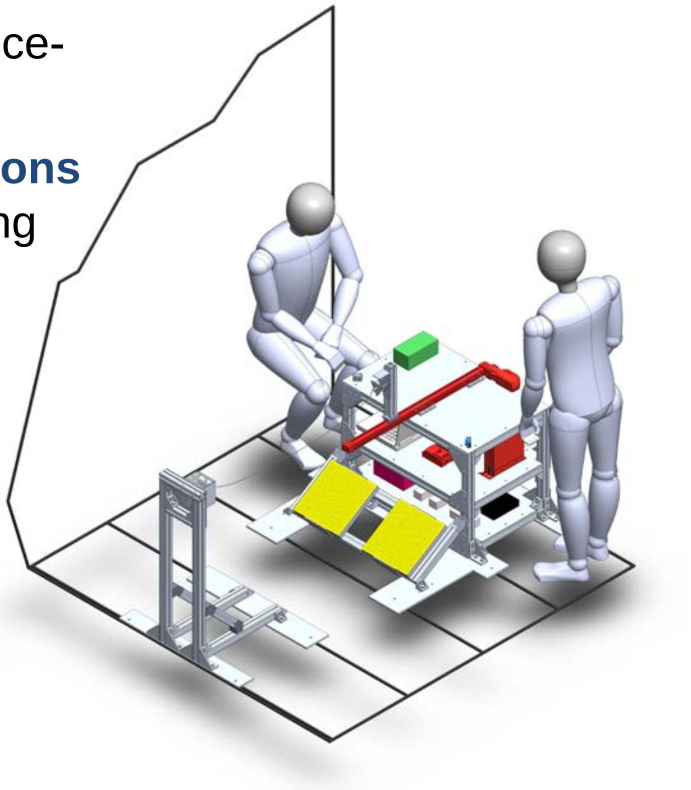
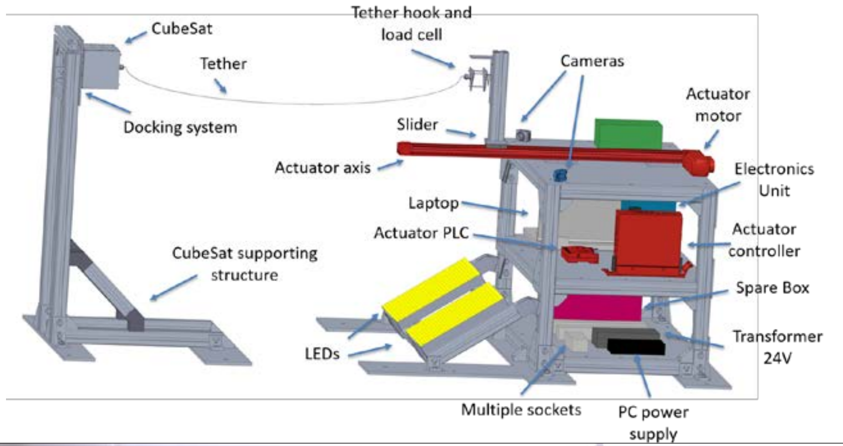
SatLeash Experiment

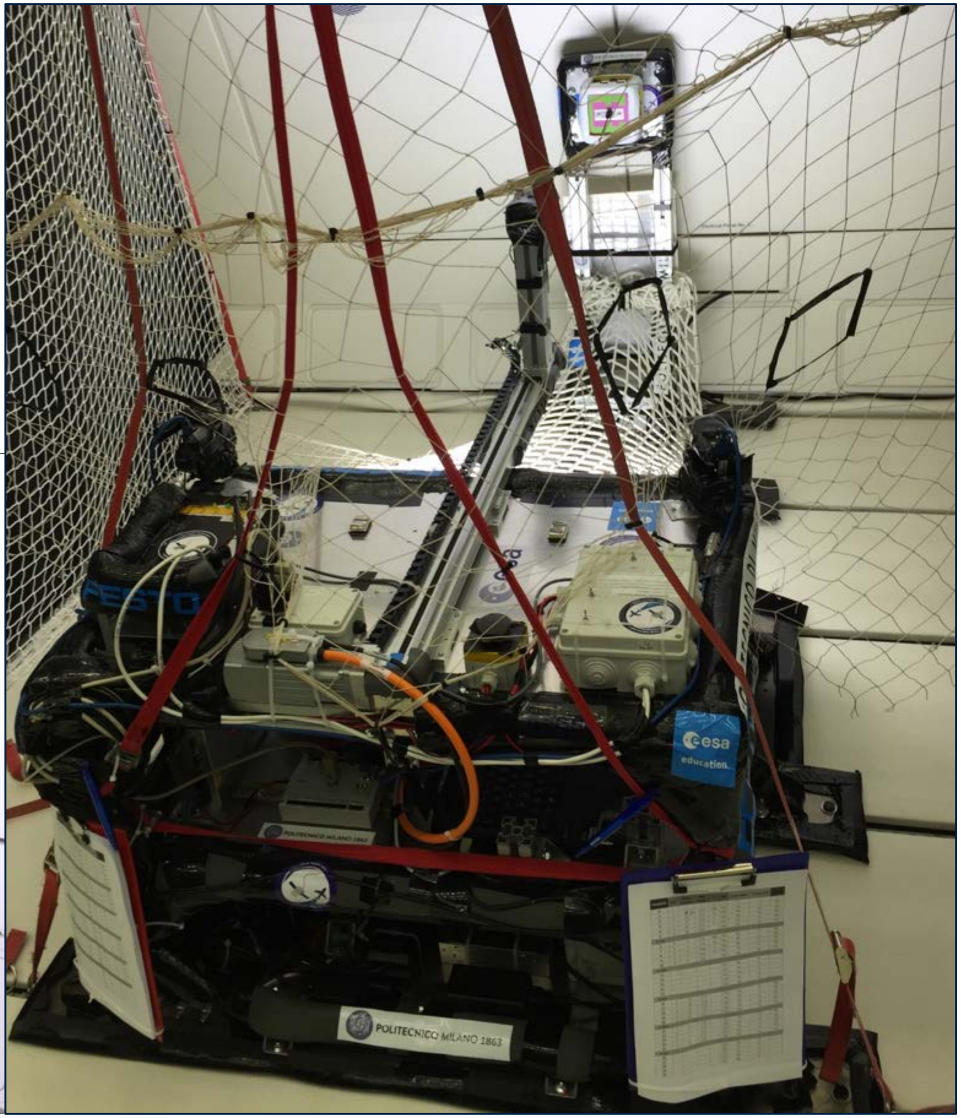
- **Objectives**
  - **Study tether's dynamics** to validate flexible elements numerical simulator
  - Study tether's **effects on the end-body** (i.e. bounce-back, wishplash)
  - **Test proposed control law for flexible connections** in orbit, and demonstrate effectiveness in stabilizing the system
  - **Increase the TRL** for a following on-orbit demonstration mission.



- **In flight experiment basics**
  - tethered system **scaled module: pulling phase reproduction**
  - **Thrust profiles** simulation by linear actuator
  - Stereo-vision + acceleration & tension sensors for **dynamics reconstruction**

SatLeash Experiment – Architecture





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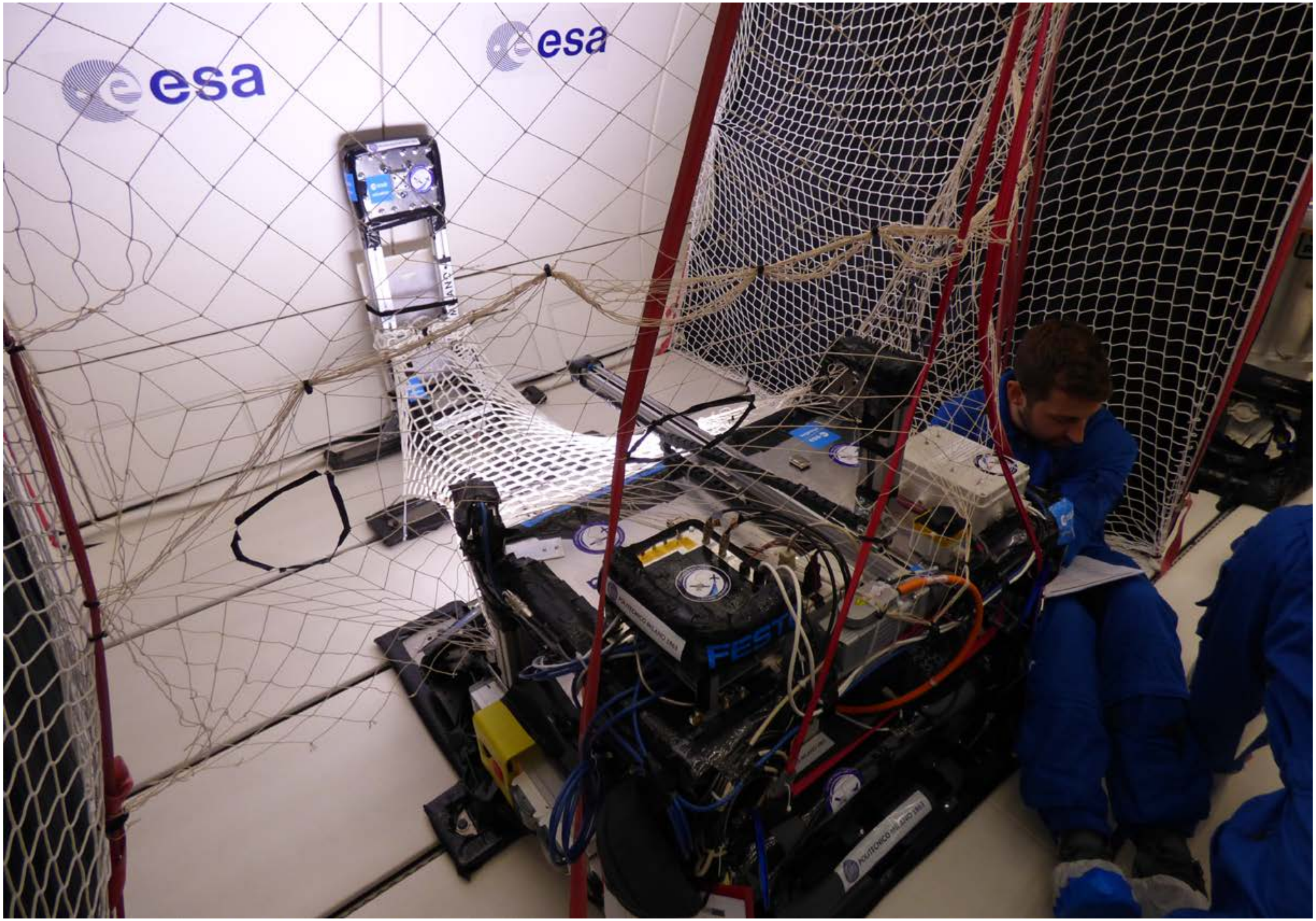

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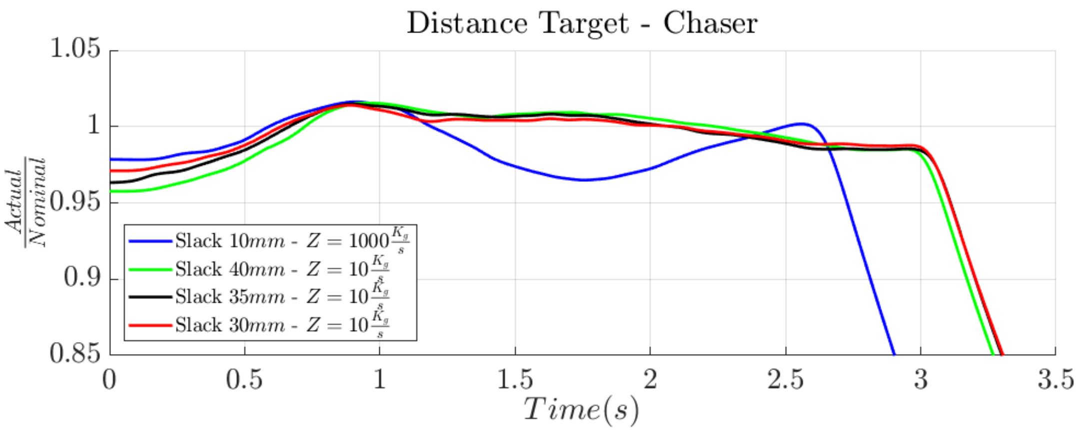
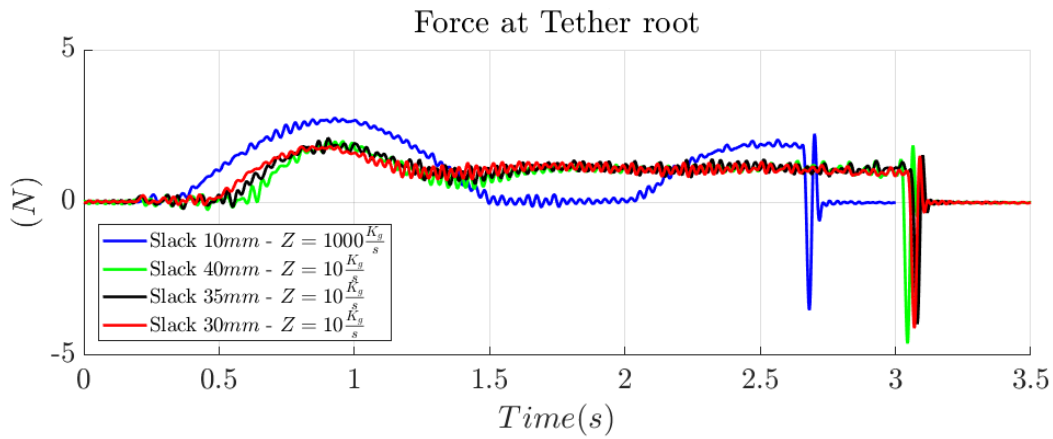
Experimental Results – Reconstruction

Experimental Results – Reconstruction

- ## Stabilization Phase





- ✓ Vibrations **with different initial slack conditions can be absorbed**
- ✓ **Overshoot** is considerably **reduced**
- ✓ **Tensioning maintained** at the end of the maneuver
- ✓ **No collapsing** of the tether observed

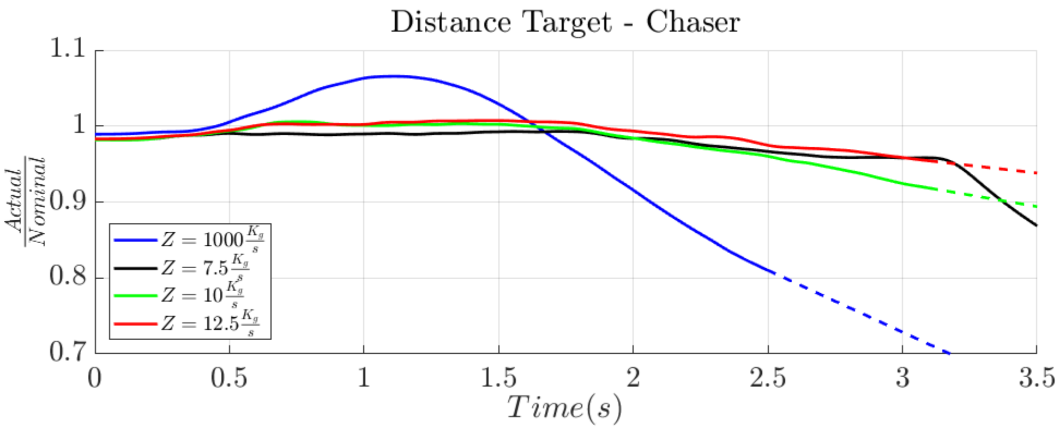
Tether Characteristics	
Material	Polyethylene
Diameter (mm)	3
Length (mm)	900

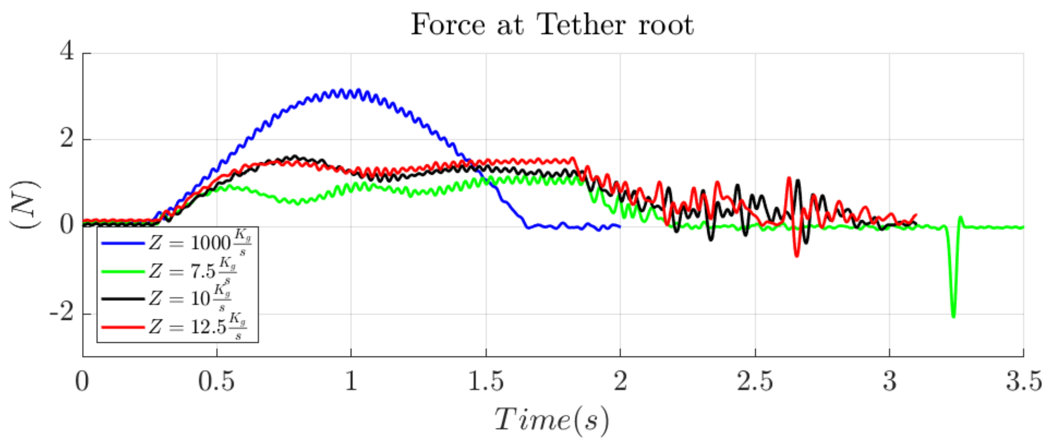
Z = $1000\frac{Kg}{s}$ → No Control

Z = $10\frac{Kg}{s}$ → Estimated Optimal value

Experimental Results – Reconstruction

- **Release Phase**





- ✓ The potential **energy elongation** coming from the tether elongation **is absorbed**
- ✓ **Relative velocity** at the maneuver end **decreases**
- ✓ **The peak of tension** is considerably **damped**
- ✓ **Control robustness**

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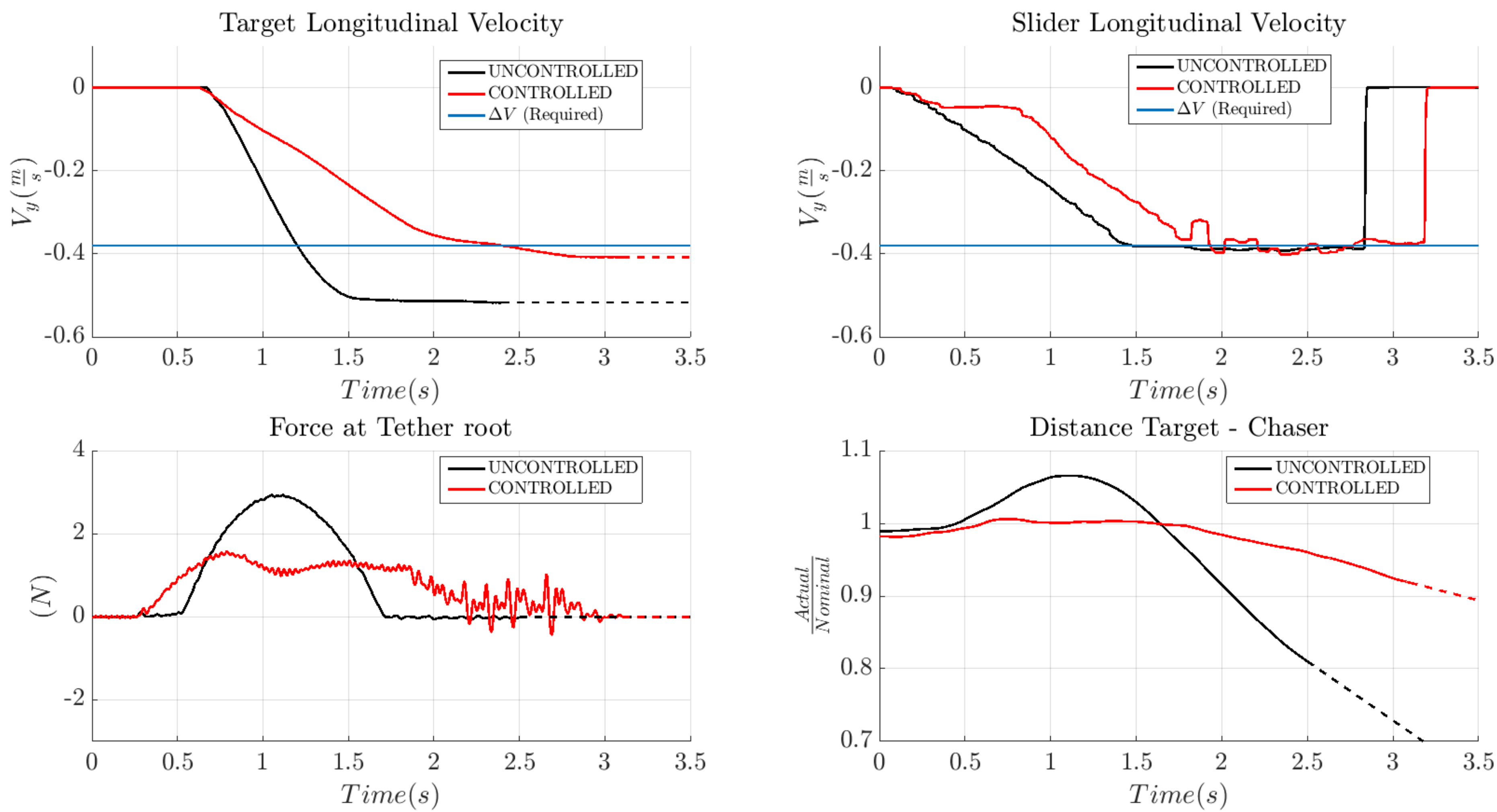
Experimental Results

- **Complete Manoeuvre**



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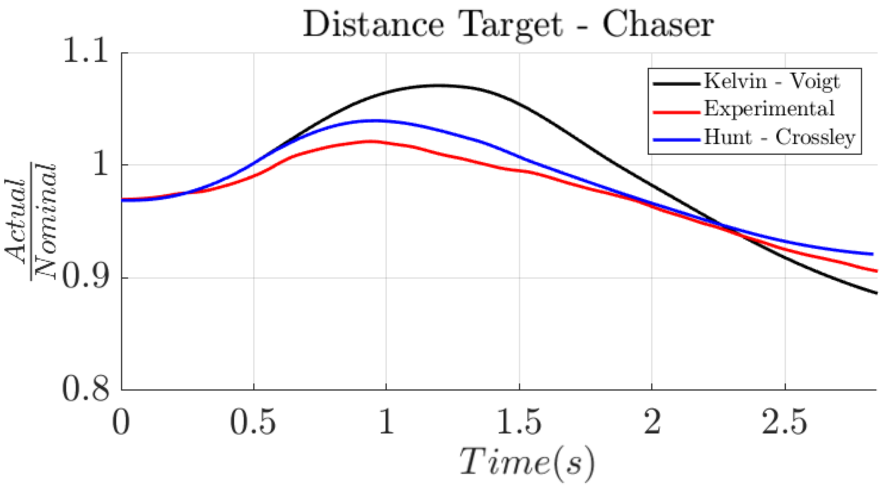
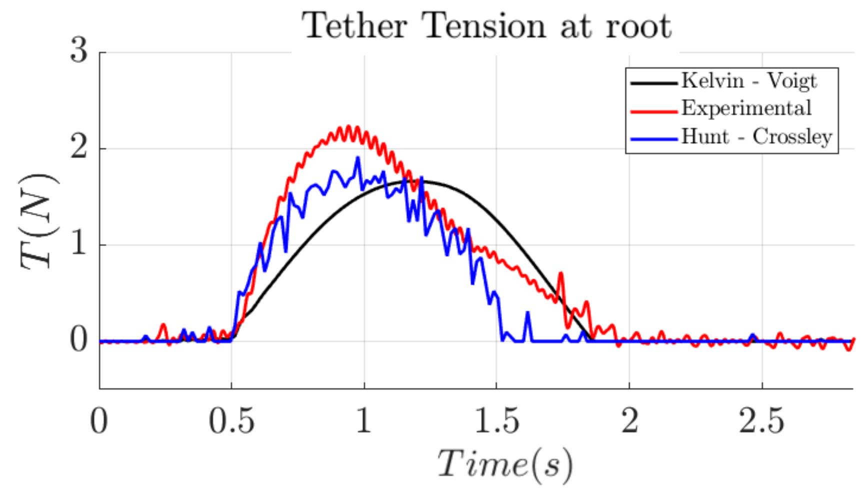
Comparison Numerical/Experimental

Parabola	Test	Z	Acc	Slack
#15 day2	Release	25	0.3	3%

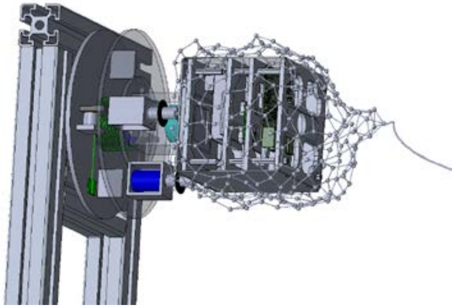




Final remarks and future work

- **Non-linear tension model** better describes the elastic tethers behaviour
- Deeper analysis are needed on Hunt-Crossley parameters selection
- **Non uniform distribution** of the **tension** inside the tether shall be investigated
- **Promising performances** for the proposed wave-based control law in both stabilization and release phase have been highlighted
- **Considerable robustness** of the wave-based control law have been confirmed

- **Full tethered-net** system in flight validation
- **Higher fidelity tether shape and tension** reconstruction from distributed sensors
- **Net-target contact forces** monitoring and reconstruction
- **Higher fidelity target dynamics representation** for control effectiviness in stack stabilization
- Different control laws and materials larger testing campaign



ADR related work

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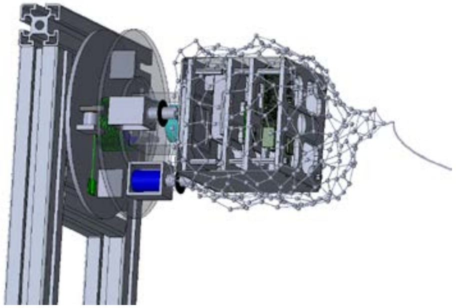

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