Spacecraft RendezVous and Docking (RVD) using electro-magnetic interactions

Ph.D. COURSE IN SPACE SCIENCES, TECHNOLOGIES AND MEASUREMENTS
Curriculum STASA - XXX CYCLE

Padova, 20 October 2017
Admission to Final Exam

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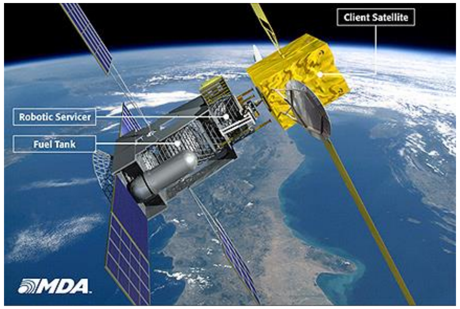
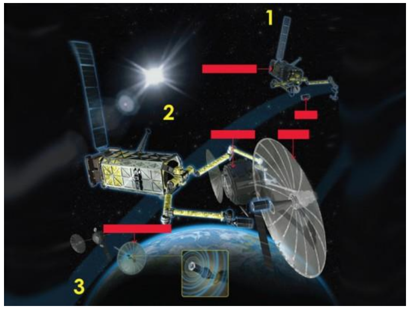
Background & motivations

Automatic on-orbit servicing (refueling, payload updating, inspection and maintenance) would allow the development of longer lifetime missions



Canadian Aerospace firm MacDonald, Dettwiler and Associates (MDA) Space Infrastructure Servicing (SIS): small scale in-space refueling depot for communication satellites

ViviSat Mission Extension Vehicle: the attitude and propulsive control for the target are supplied by chaser own thrusters



DARPA Project Phoenix program: harvest and re-use valuable components from satellites in orbit that have been retired and transport it to another satellite

DLR Space Administration DEOS: demonstrate several technologies necessary for on-orbit satellite servicing

The common missing link among the projects which can make the difference is an ***automatic RVD procedure*** which demands lower-requirements and less-accurate attitude control for proximity manoeuvres

Objectives

The goal of this research project is to study, with both numerical simulations and laboratory testing, viable strategies for *spacecraft RendezVous and Docking (RVD) manoeuvres* ***exploiting electro-magnetic interactions****.*

The ***objectives*** of this research project are:

1) the development of dynamical models of electromagnetic close formation flight for RVD applications and their verification through experiments;
2) the development and experimental verification in relevant environment (micro-gravity) of electromagnetic soft docking interfaces.

Perspective applications investigated (1/2)

Integrated system for proximity guidance and soft docking based on

MAGNETIC INTERACTIONS

Position and
Attitude
Control with
MAgnetic
Navigation

PACMAN

Designed to be tested in relevant environment

Spacecraft joining using a

TETHERED ELECTROMAGNETIC PROBE

TED

New docking concept

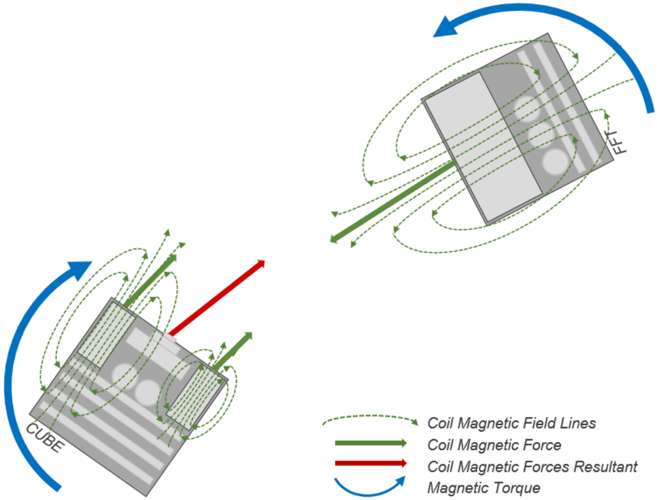
Tethered
Electromagnetic
Docking

Perspective applications investigated (2/2)

PACMAN

Features

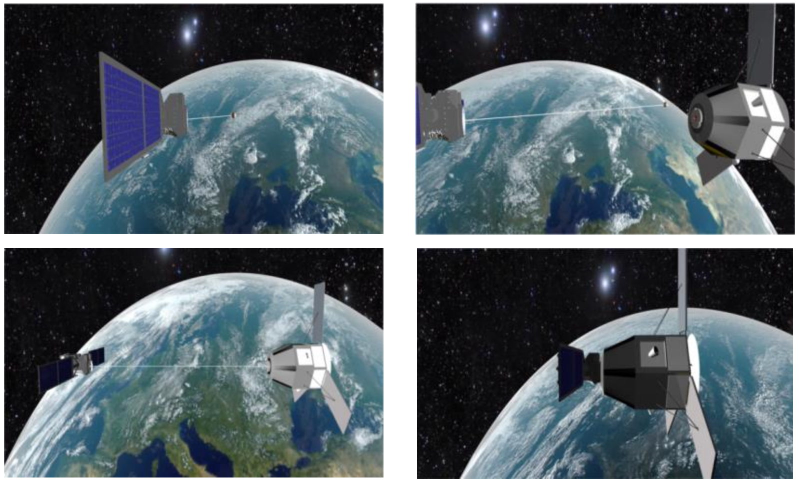
1) Miniature spacecraft mock-up (CUBE) and a Free-Floating Target (FFT) that generates a static magnetic field
2) Actively-controlled magnetic coils on-board the CUBE, assisted by dedicated localization sensors, used to control its attitude and relative position assuring the accomplishment of the soft docking manoeuvre



TED

Features

1) Tethered electromagnetic probe ejected by the chaser toward a receiving electromagnetic interface mounted on the target spacecraft
2) Automatic alignment between the two interfaces exploiting the magnetic interactions
3) Hard docking accomplished by tether retrieval



OUTLINE

PACMAN experiment

- PACMAN objectives
- Parabolic flight
- Experiment overview
  - CHAMBER
  - CUBE
  - FFT
- Dynamic simulations
- Magnetic coil test
- On-board camera test

TED

- Tether model
- Tether deployment
- Electromagnetic probe model
- Rendezvous manoeuvre & soft-docking simulations
- Experimental test & result

PACMAN experiment

PACMAN
EXPERIMENT
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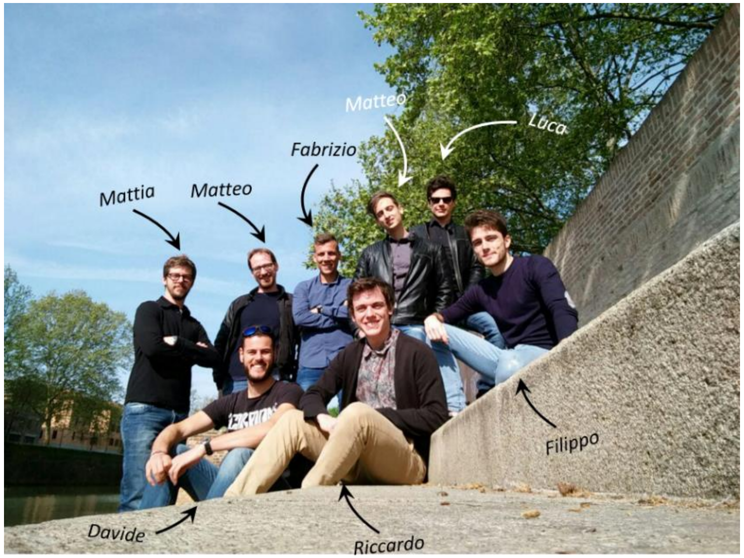


PACMAN objectives

Develop a system for CubeSat **proximity guidance and soft docking** exploiting magnetic interaction

Develop a dedicated low-range sensors system based on markers/camera for **relative range and attitude estimation**

Validate the whole PACMAN system in a relevant low-gravity environment

Parabolic flight

Experiment overview

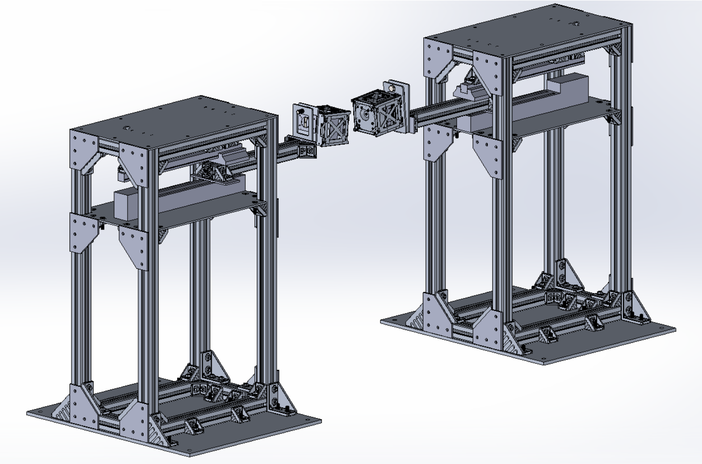
PACMAN is composed by four main subsystems:

1) CHAMBER - a testing chamber in which the CUBE and the FFT will float freely; it is equipped with two launch systems, an external stereo-camera and an IMU board

2) CUBE - 1U CubeSat equipped with sensors and actuators for proximity GNC

3) FFT - 1U CubeSat equipped with a target electromagnet (docking interface)

4) Laptop for experiment monitoring and "external remote control" via software



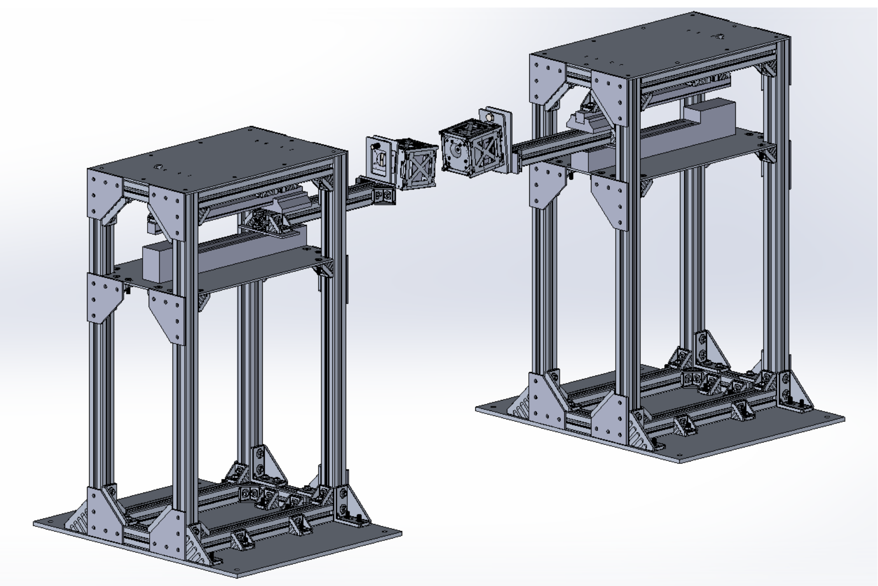
1 CHAMBER

The CHAMBER is a safe environment for the CUBE and the FFT to float as it avoids the risk of hurting other people, damaging the experiments or the support electronics, equipped with

Two racks with two hold & launch systems which launch the CUBE and the FFT one towards the other

One external reference stereo-camera

IMU



to acquire images of the CUBE and the FFT during the floating phase of the experiment

to acquire information about the airplane motion

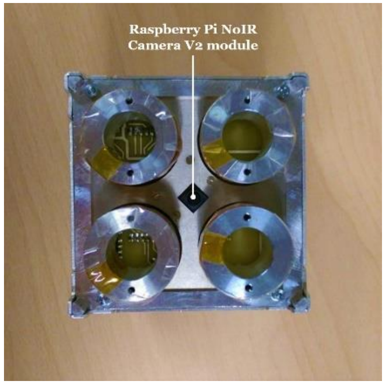
PACMAN experiment

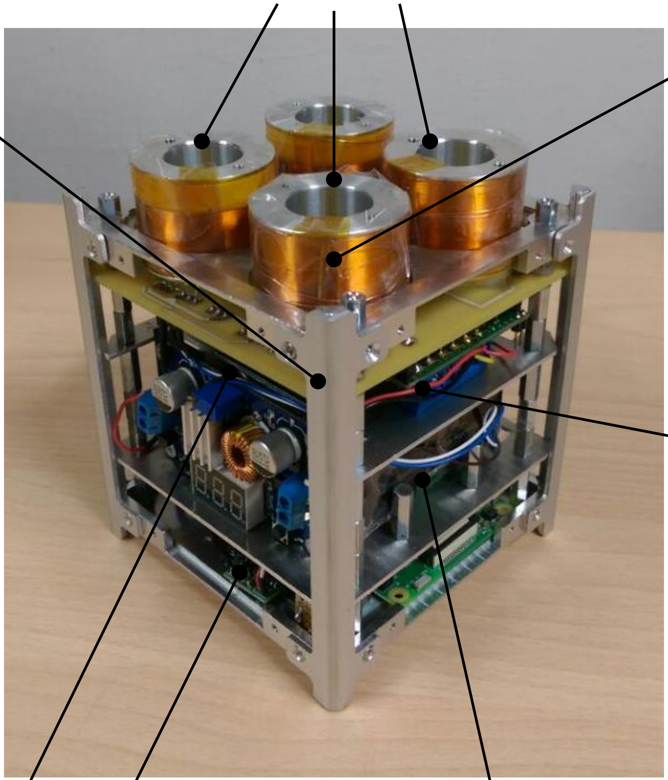
2 CUBE

The IMU Board is used to obtain information of the pose

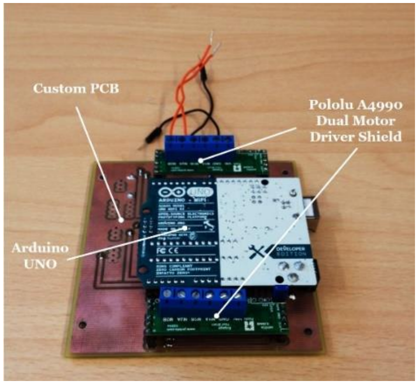
The Magnetic Coils are used as actuators of the rendezvous/attitude control system

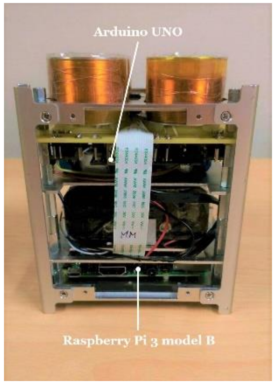
The On-board Camera is used for visual relative pose (position/attitude) determination





Driver Circuit to supply the proper voltage to the Magnetic Coils



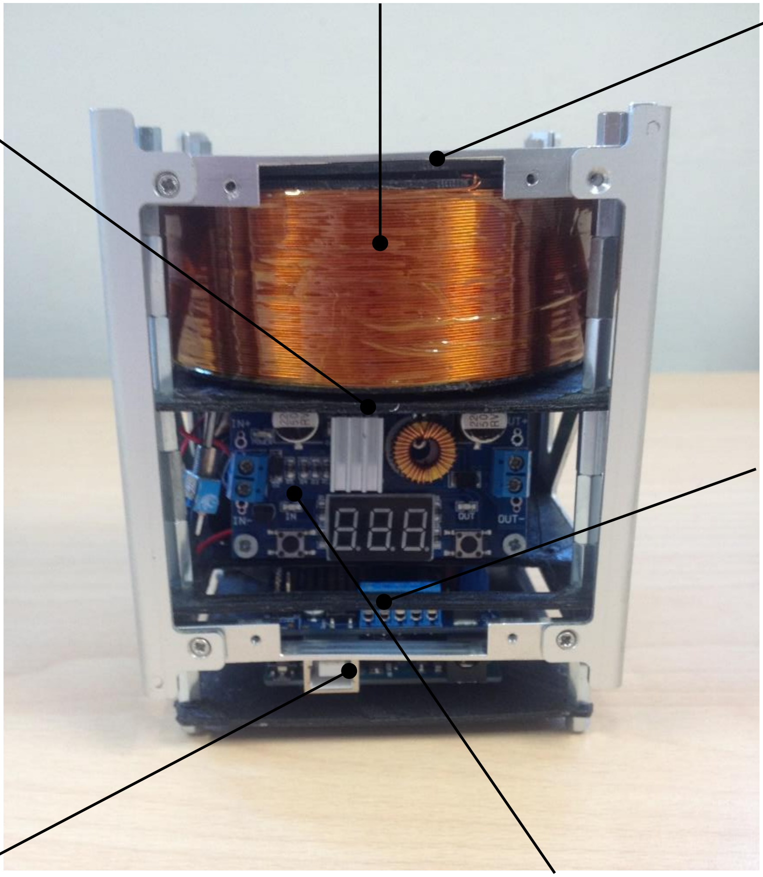


The Microcontroller Boards are used for control logic, sensor reading and data handling. Raspberry PI 3 Model B to manage video data obtained from the On-board Camera. Arduino UNO to collect, store and process all the data coming from the sensors on-board the CUBE

One Battery Pack to provide power to the Electronic Boards and to the Magnetic Coils.

PACMAN experiment

3 FFT



The Magnetic Coil is used as docking interface

5 Leds are located on the docking interface to ease the FFT detection by the camera on board the CUBE

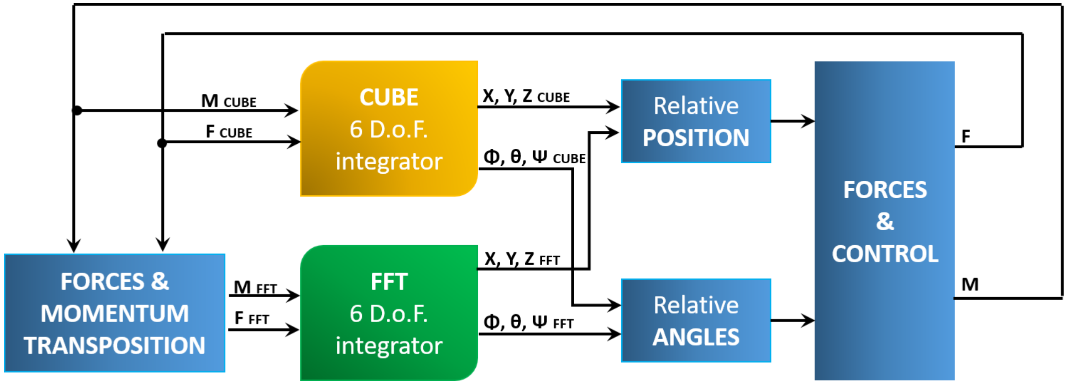
The IMU Board is used to obtain information about the entire systems dynamics

Driver Circuit to supply the proper voltage to the Magnetic Coil

The Microcontroller Board is used to power the coil and the leds

One Battery Pack to provide power to the Electronic Boards and to the Magnetic Coil

Dynamic simulations



M CUBE

F CUBE

CUBE
6 D.o.F.
integrator

X, Y, Z CUBE

Φ, θ, Ψ CUBE

Relative
POSITION

FORCES
&
CONTROL

F

M

FORCES &
MOMENTUM
TRANSPOSITION

M FFT

F FFT

FFT
6 D.o.F.
integrator

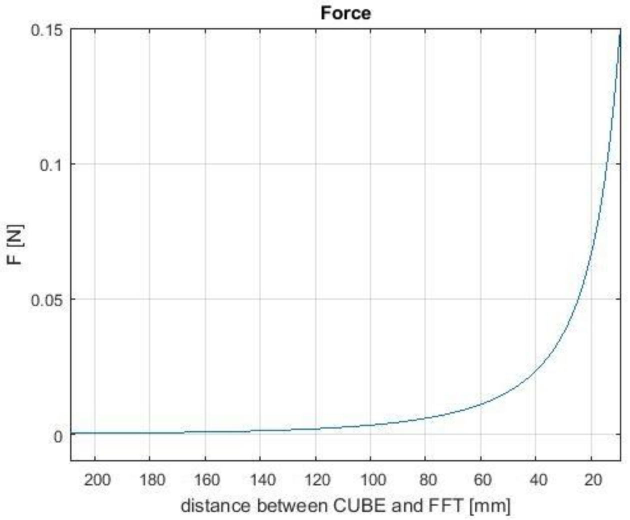
X, Y, Z FFT

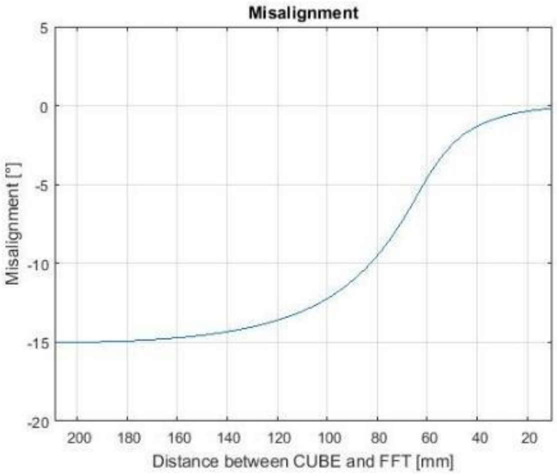
Φ, θ, Ψ FFT

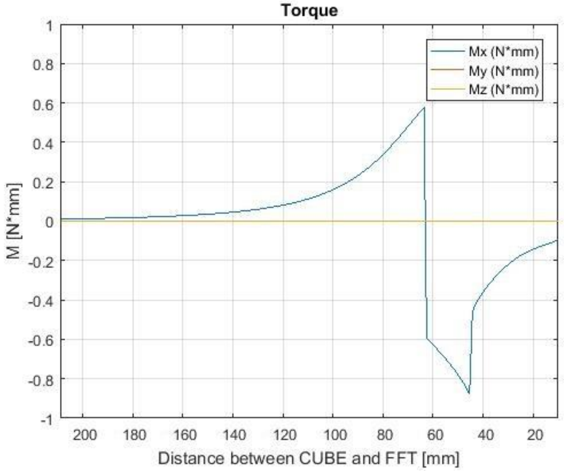
Relative
ANGLES

Parameters:

- Diameter$_{cube\_coils}$ = 36 mm
- Diameter$_{fft\_coil}$ = 100 mm
- MagnetoMotiveForce$_{cube\_coils}$ = 100 A/turns (for each coil)
- MagnetoMotiveForce$_{fft\_coils}$ = 450 A/turns

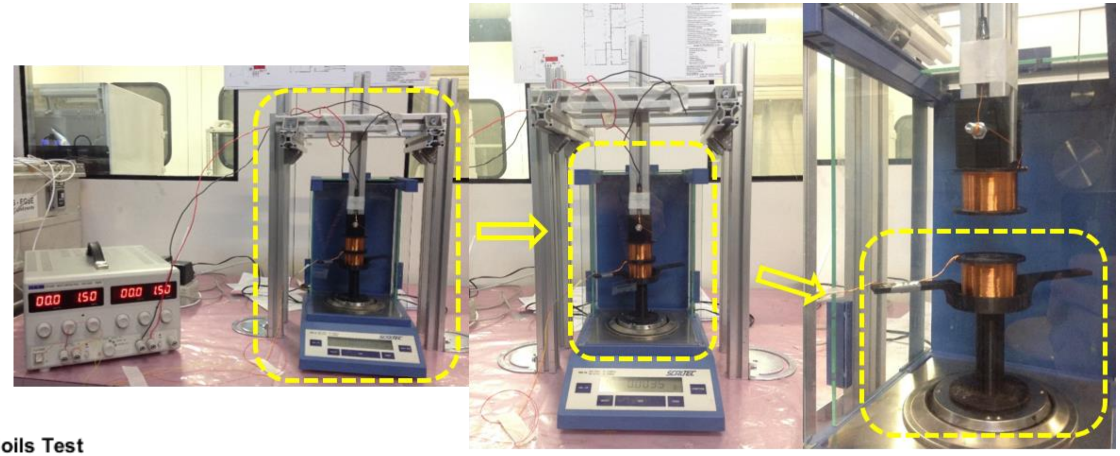


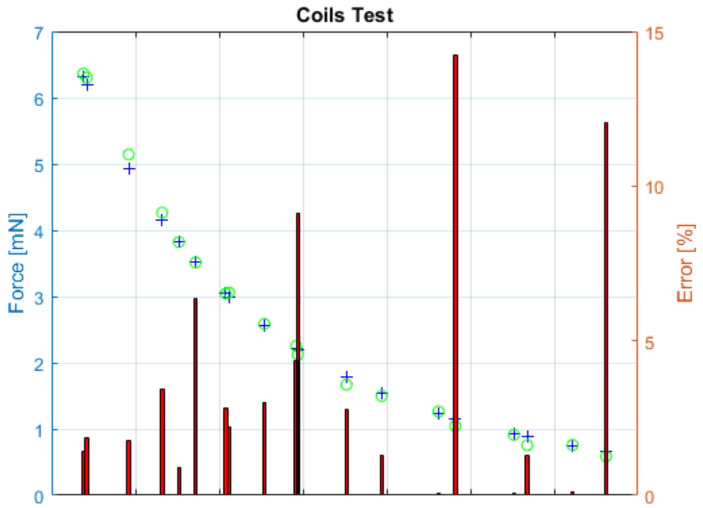




Magnetic coil test

Very precise scale (accuracy 0.0001 g) used to measure the repellant force between two coils

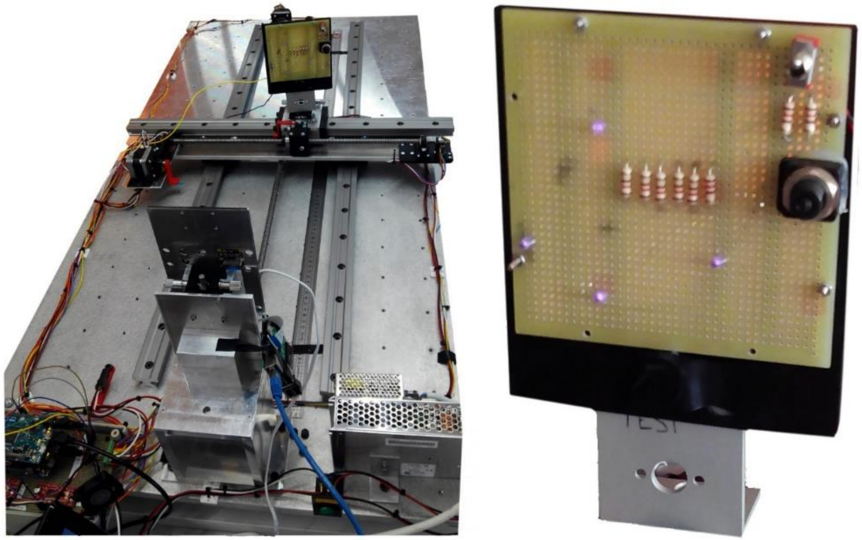


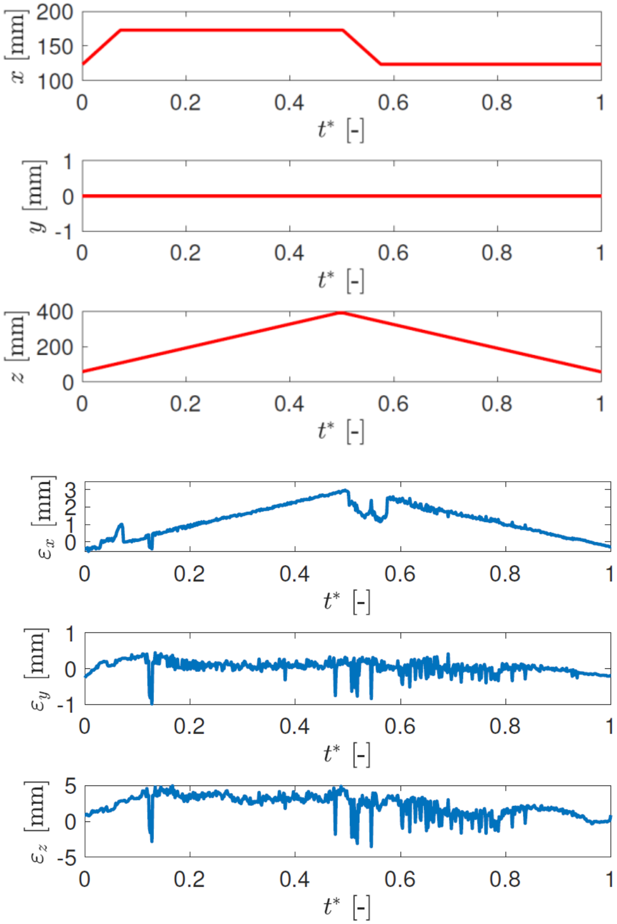


- Green circles: force measured [mN]
- Blue crosses: force obtained from the model [mN]
- Red bars relative error [%].

On-board camera test

- Target mock-up mounted on two high precision motorized linear stages and a rotary stage
- The linear stages impose the planar displacements to the target mock-up while the rotary stage allows the rotations
- The camera acquires images at a resolution of 1280 x 960 pixel with a field of view of 62.2° x 48.8°
- The pose of the target can be measured by means of the vision system and then compared to the imposed motion





	μ [deg]	σ [deg]
Roll (ϕ)	2.79	4.61
Pitch (ϑ)	0.04	2.69
Roll (ψ)	-1.26	0.29

OUTLINE

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TED

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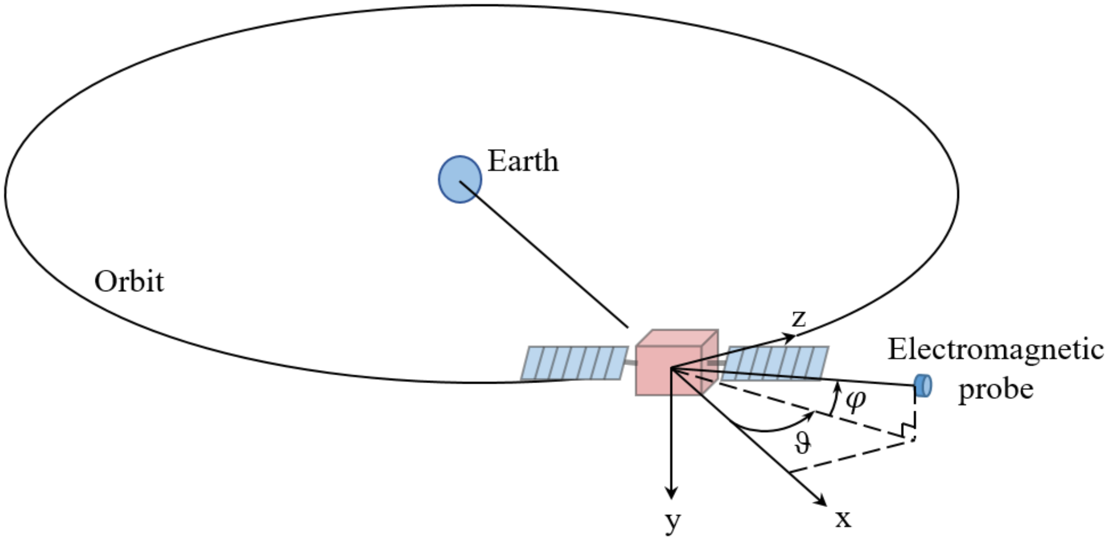
Tether model

Varying length dumbbell model

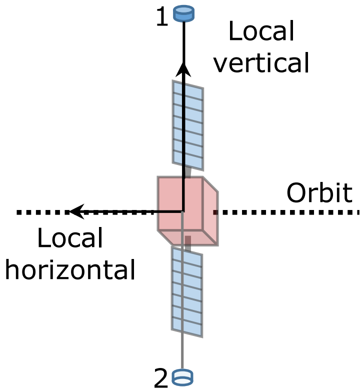


Attitude

Described by three variables: length *l*, in-plane libration angle θ and out-of-plane libration angle φ

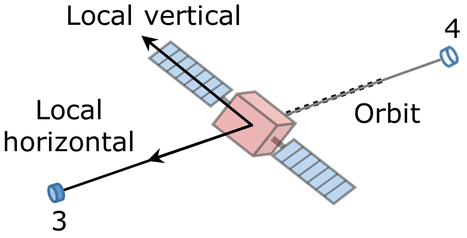
Tether deployment

2
Along the local vertical
(R-bar approach, STABLE)



Electromagnetic probe with relevant velocity
Docking manoeuvre performed once per orbit

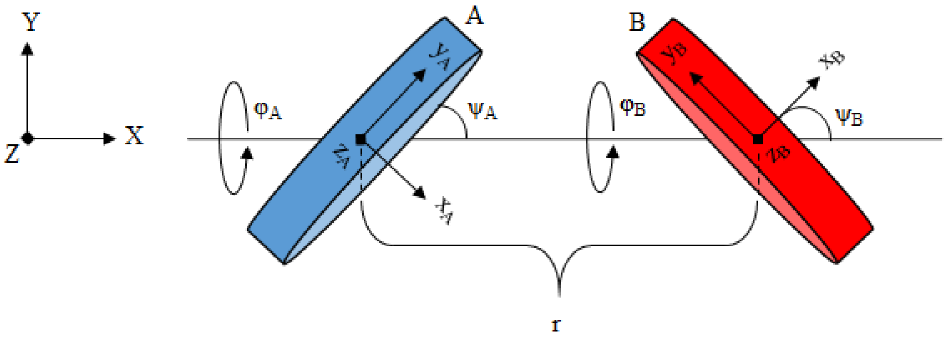
2
Along the local horizontal
(V-bar approach, UNSTABLE)



Reliability: in case of an unsuccessful deployment, the tether can be rewound and deployed again without waiting an entire orbital period

Electromagnetic probe model (1/2)

- The exact solution of the magnetic field equations contains integrals that cannot be solved analytically
- The first order expansion of the Taylor series is known as the far-field model (or magnetic dipole assumption)
- This model provides an analytical solution and it is easy to implement



Attitude

Described through the second cardinal equation and the magnetic interaction between the dipoles

Electromagnetic probe model (2/2)

Probe characteristics

- guarantee the adaptability with the target interface
- maximize the effect of the magnetic guidance
- have a reduced mass
- have the lowest power consumption and volume possible

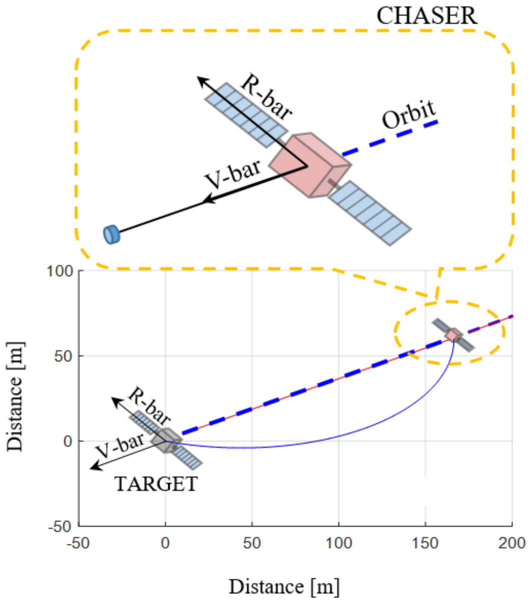
To guarantee all the aforementioned features, the electromagnetic interface aboard the target and the coil inside the probe have different characteristics

Target	Probe
Diameter: 100 mm	*Diameter: 50 mm*
Turns: 700	*Turns: 300*
Mass: 1.2 kg	*Mass: 0.24 kg*
Power consumption: 5 W	*Power consumption: 1 W*

Rendezvous manoeuvre & soft-docking simulation

V-bar Approach

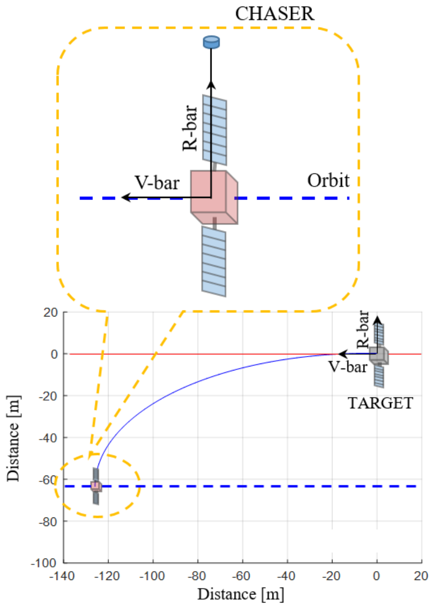
Spacecraft orbit: circular (600 km)
Distance Target-Chaser: 175.4 m



Deployment velocity of the tether: 0.075 m/s
Total deployment time: 1786 s (~ 30 min)
Final tether length: 176 m

R-bar Approach

Spacecraft orbit: circular (600 and 600.06025 km)
Distance Target-Chaser: 60.25 m

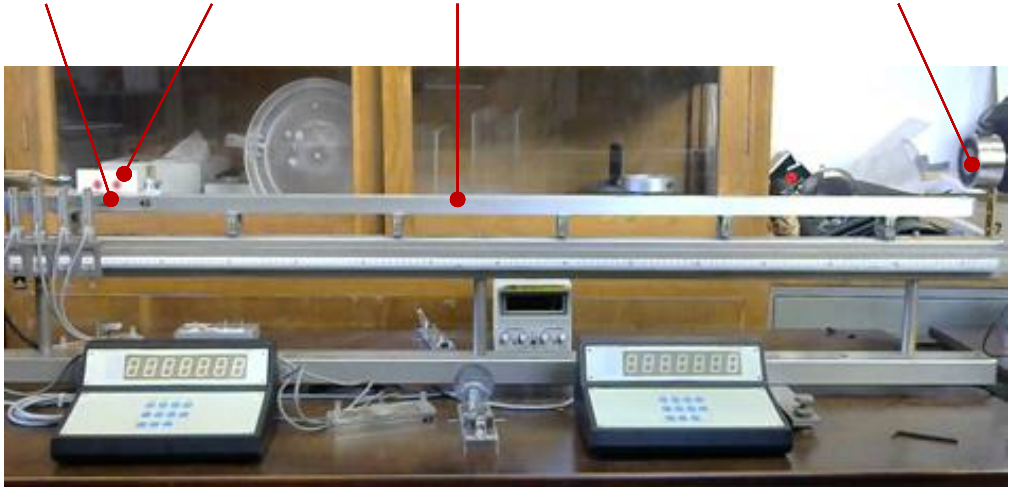


Deployment velocity of the tether: 0.075 m/s
Total deployment time: 1458s (~ 25 min)
Final tether length: 146.4 m

Experimental test & results

Laboratory setup:

- An air-cushion low-friction rail
- A sled equipped with
  - two square markers used to track its position
  - an iron plate as interface to interact with the electromagnetic field produced by the electromagnet
- An electromagnet positioned at one end of the rail

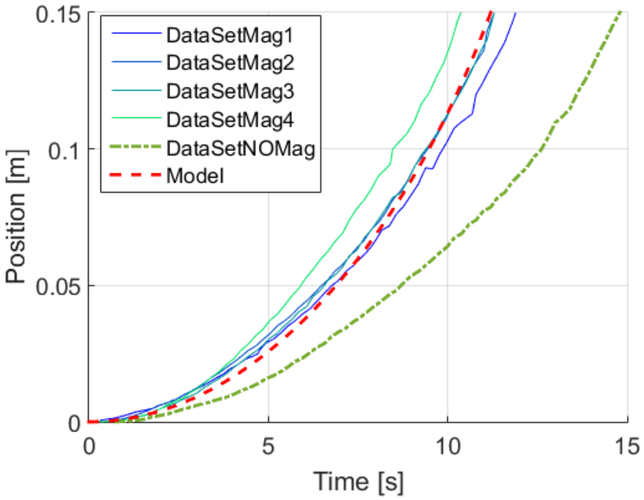


Sled

Markers

Low-friction rail

Electromagnet



Conclusions & future works

- The realization of the PACMAN experiment will allow to:
    - validate the theoretical/numerical models that describe the CUBE/FFT interactions
    - assess the system concept feasibility and its limitations
    - improve the proposed technology for future developments

- Tethered Electromagnetic Docking is proposed as effective solution to perform a soft-docking manoeuvre:
    - The R-bar approach benefits of the tether deployment stabilization along the local vertical
    - The V-bar approach is easier and guarantees the repeatability of the manoeuvre
    - Some preliminary tests have been carried out to verify the reliability of the numerical model used

EXTRA

ARTICLES

1. D. Petrillo, M. Gaino, **M. Duzzi**, G. Grassi, A. Francesconi (2017). TETHERED DOCKING SYSTEMS: ADVANCES FROM FELDs EXPERIMENT. In publication: Acta Astronautica.

CONFERENCE PAPERS

1. **G. Grassi, A. Gloder, L. Pellegrina, M. Pezzato, A. Rossi, F. Branz, **M. Duzzi**, R. Mantellato, L. Olivieri, F. Sansone, E. C. Lorenzini, A. Francesconi (2017). AN INNOVATIVE SPACE TETHER DEPLOYER WITH RETRIEVAL CAPABILITY: DESIGN AND TEST OF STAR EXPERIMENT. In 68th International Astronautical Congress. Adelaide, 25-29 September 2017.
2. L. Olivieri, A. Antonello, L. Bettiol, F. Branz, **M. Duzzi**, F. Feltrin, G. Grassi, R. Mantellato, F. Sansone, A. Francesconi (2017) MICROGRAVITY TESTS IN PREPARATION OF A TETHERED ELECTROMAGNETIC DOCKING SPACE DEMONSTRATION. In 68th International Astronautical Congress. Adelaide, 25-29 September 2017.
3. L. Olivieri, F. Branz, **M. Duzzi**, R. Mantellato, G. Grassi, F. Sansone, A. Francesconi (2017). TECHNOLOGIES TO JOIN SPACECRAFT USING A TETHERED ELECTROMAGNETIC PROBE. In AIDAA XXIV International Conference. Palermo – Enna, 18-22 September 2017.
4. **M. Duzzi**, R. Casagrande, M. Mazzucato, F. Trevisi, F. Vitellino, M. Vitturi, A. Cenedese, A. Francesconi (2017). ELECTROMAGNETIC POSITION AND ATTITUDE CONTROL FOR PACMAN EXPERIMENT. In 10th International ESA Conference on Guidance, Navigation & Control Systems. Salzburg, 29 May - 2 June, Austria.
5. **M. Duzzi**, G. Grassi, L. Olivieri, A. Francesconi. SPACECRAFT JOINING USING A TETHERED ELECTROMAGNETIC PROBE. In 67th International Astronautical Congress. Guadalajara, 26-30 September 2016.
6. D. Petrillo, M. Gaino, **M. Duzzi**, G. Grassi, A. Francesconi. TETHERED DOCKING SYSTEMS: ADVANCES FROM FELDs EXPERIMENT. In 67th International Astronautical Congress. Guadalajara, 26-30 September 2016.
7. **M. Duzzi**, L. Olivieri, A. Francesconi (2016). TETHER-AIDED SPACECRAFT DOCKING PROCEDURE. In: 4S Symposium (Small Satellites, Systems & Services). La Valletta, 30 May – 03 June 2016, Malta.
8. **M. Duzzi**, L. Olivieri, A. Francesconi (2015). SCRAT EXPERIMENT: A STUDENT EXPERIENCE. In: 1st Symposium on Space Educational Activities. Padova, 9-11 December 2015.
9. L. Olivieri, F. Branz, **M. Duzzi**, R. Mantellato, F. Sansone, E. C. Lorenzini, A. Francesconi (2015). TETHERED ELECTROMAGNETIC CAPTURE: A CUBESAT MISSION CONCEPT. In: 66th International Astronautical Cogress. Jerusalem, 12-16 October 2015.
10. L. Bettiol, F. Branz, A. Carron, **M. Duzzi**, A. Francesconi (2015). NUMERICAL SIMULATIONS ON A SMART CONTROL SYSTEM FOR MEMBRANE STRUCTURES. In: 66th International Astronautical Cogress. Jerusalem, 12-16 October 2015.
11. L. Olivieri, A. Antonello, **M. Duzzi**, F. Sansone, A.Francesconi (2015). SEMI-ANDROGYNOUS MULTIFUNCTIONAL INTERFACE FOR EXPANDABLE SPACE STRUCTURES. In: 66th International Astronautical Cogress. Jerusalem, 12-16 October 2015.

** winner of the "**Hans von Muldau Team Award for the Best Team Project**" during the International Astronautical Congress (IAC) 2017 in Adelaide, Australia.

THANK YOU FOR YOUR KIND ATTENTION!
ANY QUESTIONS?

CISAS
G. COLOMBO

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