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

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

Padova, 16 September 2016
Admission to III year

Ph.D. Candidate: Matteo Duzzi
Supervisor: Prof. Alessandro Francesconi

CISAS G. COLOMBO
SSG UNIVERSITY OF PADOVA
UNIVERSITÀ DEGLI STUDI DI PADOVA

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

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

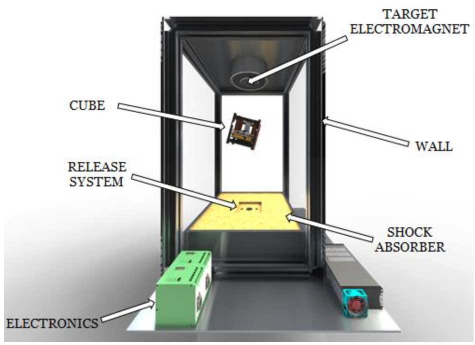
Tethered
Electromagnetic
Docking

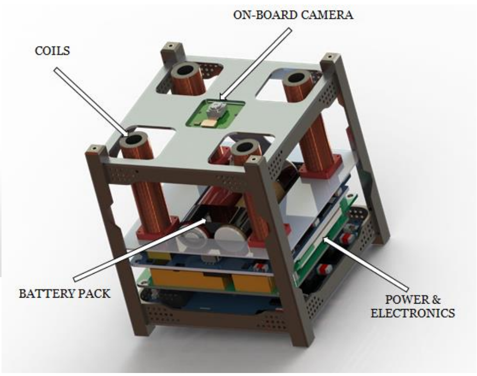
Perspective Applications Investigated

PACMAN

Features

1) A testing chamber in which a 1U CubeSat will be free to float
2) 1U CubeSat equipped with a closed-loop system for proximity guidance based on electromagnetic coils
3) SUPPORT ELECTRONICS for experiment monitoring and "external remote control"

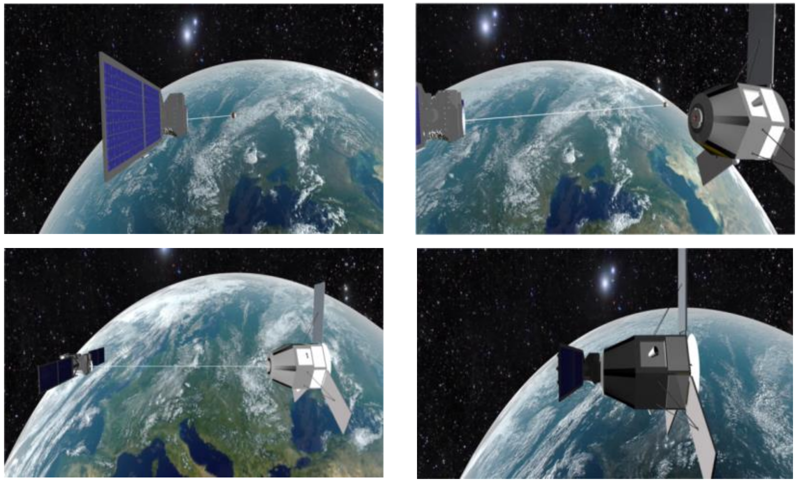




TED

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



CONTENT

Work Done

Objective 1

- ✓ Electromagnetic interactions
  - ❑ Dipole model
  - ❑ Dipoles dynamics
- ✓ Tether
  - ❑ Dumbell model
  - ❑ Deployment dynamics
- ✓ TED simulations

5 months

Objective 2

- ✓ Experimental setup
  - ❑ ESA Drop Your Thesis programme: PACMAN
  - ❑ ESA Fly Your Thesis programme: PACMAN Pre-Selection
  - ❑ Low friction table
- ✓ Activities connected to the research
  - ❑ OnOrbit project

4 months

Current situation

- ✓ ESA Fly Your Thesis programme

→ 1 month

Future works

CONTENT

Work Done

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4 months

Current situation

- ✓ ESA Fly Your Thesis programme

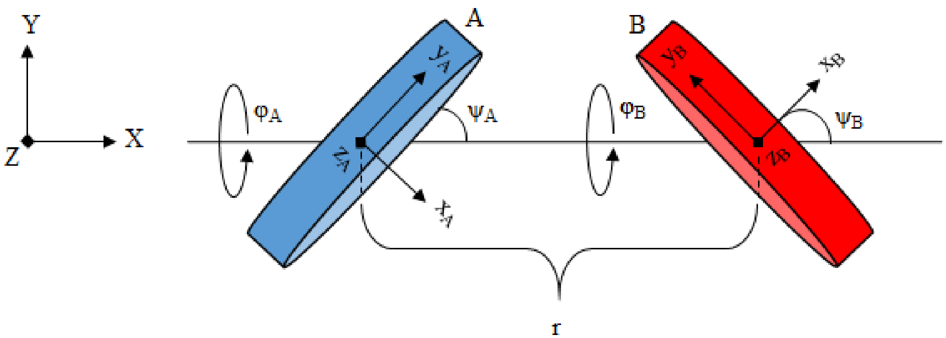
→ 1 month

Future works

Electromagnetic interactions

Dipole model

- 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

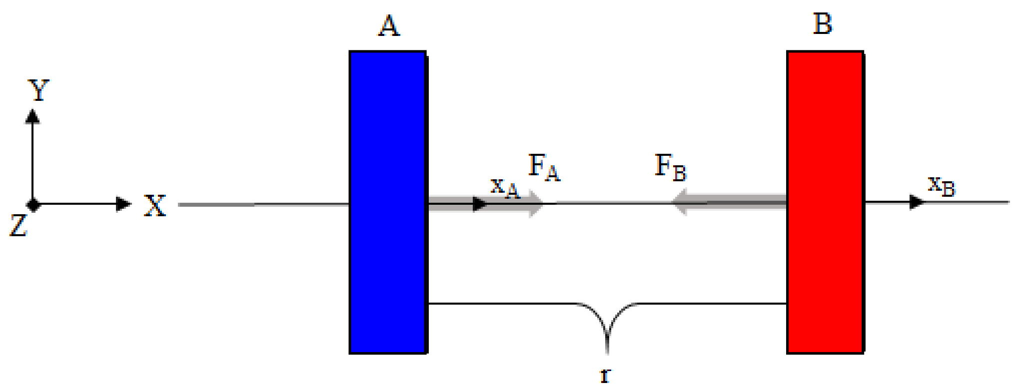


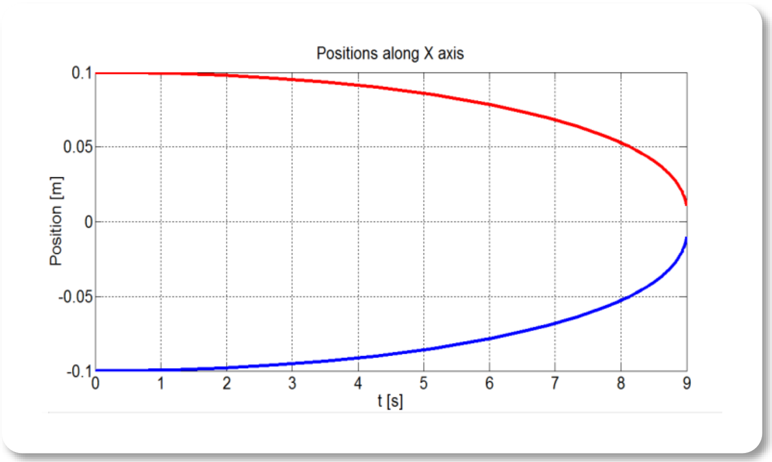
Attitude

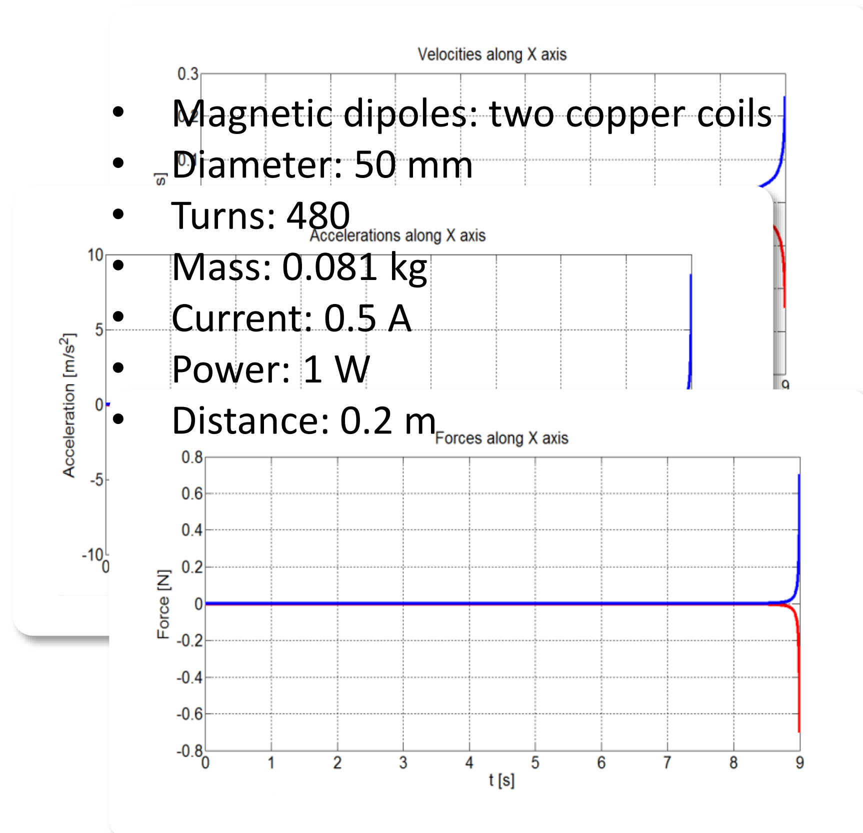
Described through the second cardinal equation and the magnetic interaction between the dipoles

Electromagnetic interactions

Dipoles dynamics



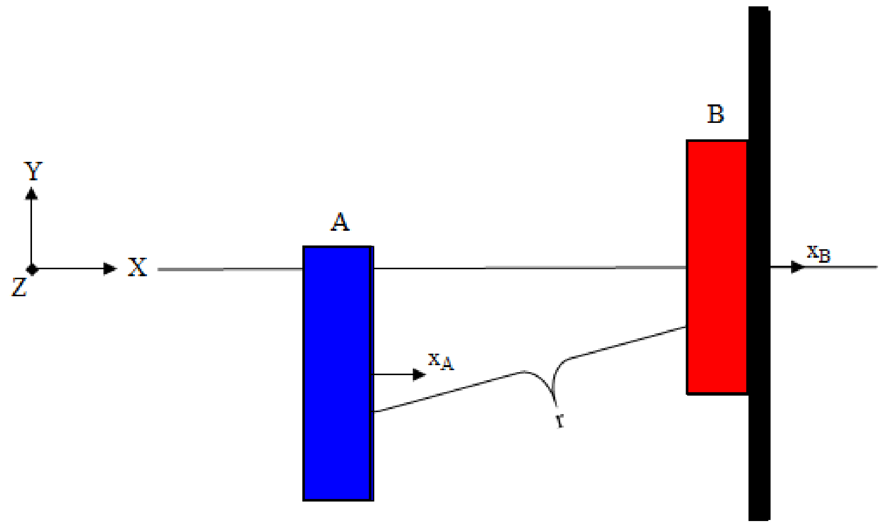


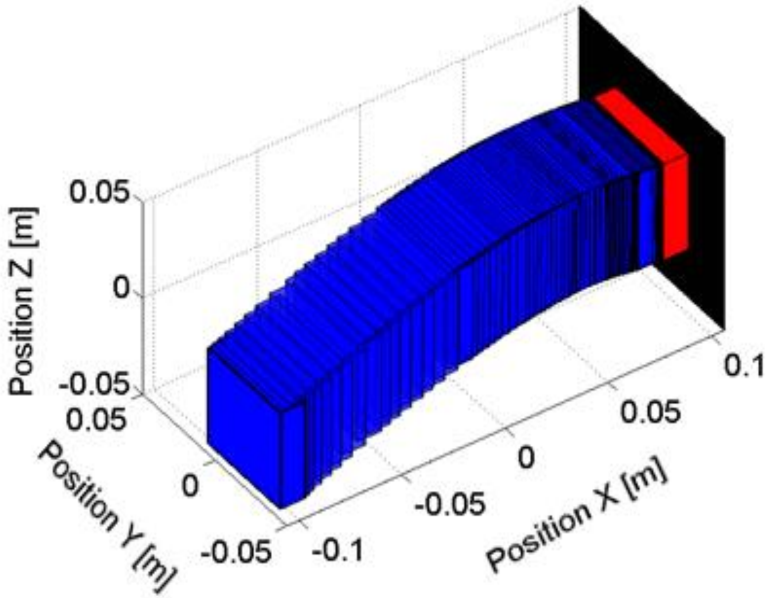


- Magnetic dipoles: two copper coils
- Diameter: 50 mm
- Turns: 480
- Mass: 0.081 kg
- Current: 0.5 A
- Power: 1 W
- Distance: 0.2 m

Electromagnetic interactions

Dipoles dynamics

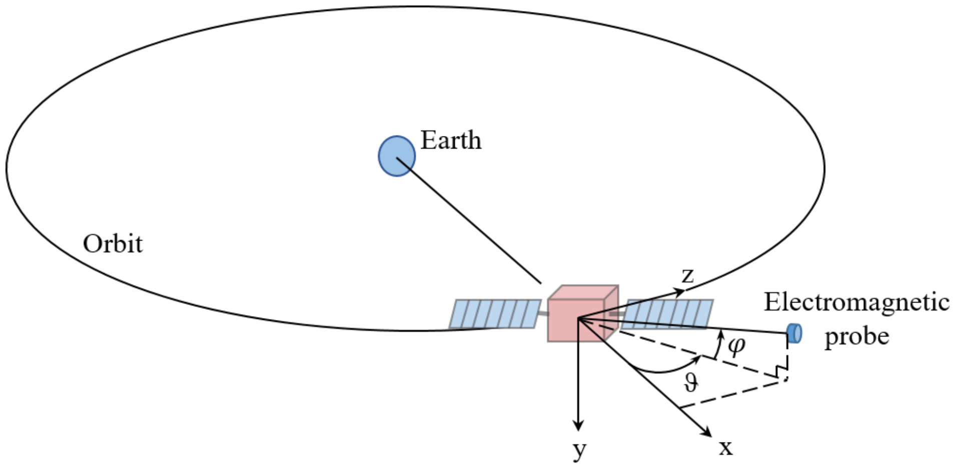




- Magnetic dipoles: two copper coils
- Diameter: 50 mm
- Turns: 480
- Mass: 0.081 kg
- Current: 0.5 A
- Power: 1 W
- Probe c.o.m.: (-0.1,-0.02,-0.02) m

Tether

Varyng length dumbbell model



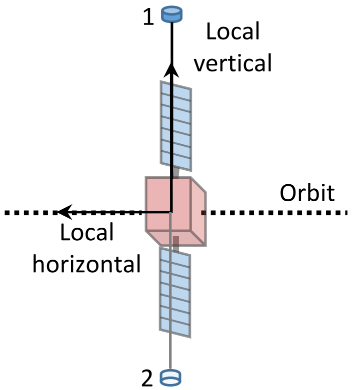
Attitude

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

Tether

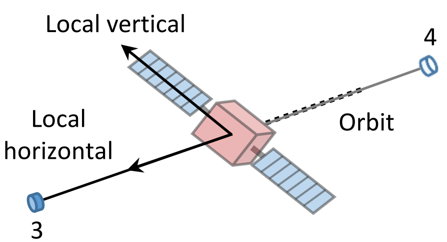
Deployment Dynamics

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)

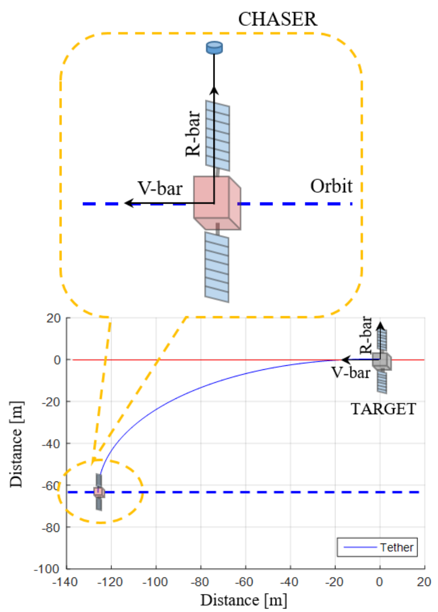


Reliability: in case of an unsuccessful deployment, the tether can be rewound and deployed again without waiting an entire orbital period

TED Simulations

R-bar Approach

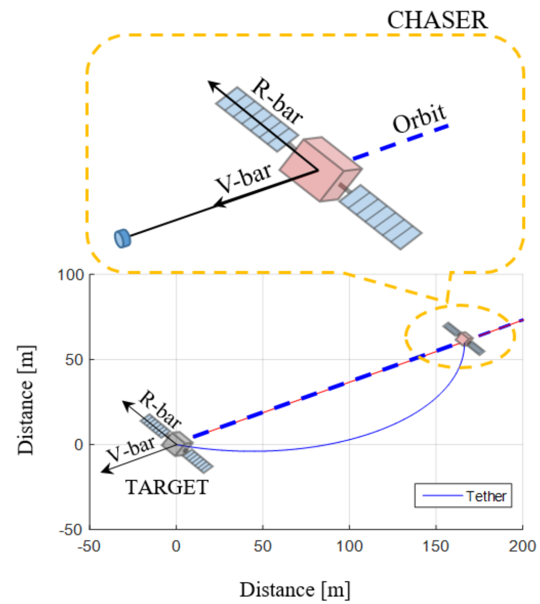
Spacecraft orbit: circular (600 and 600.06025 km)
Distance Target-Chaser: 60.25 m



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

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

CONTENT

Work Done

Objective 1

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- ✓ TED simulations

5 months

Objective 2

- ✓ Experimental setup
  - ❑ ESA Drop Your Thesis programme: PACMAN
  - ❑ ESA Fly Your Thesis programme: PACMAN Pre-Selection
  - ❑ Low friction table
- ✓ Activities connected to the research
  - ❑ OnOrbit project

4 months

Current situation

- ✓ ESA Fly Your Thesis programme

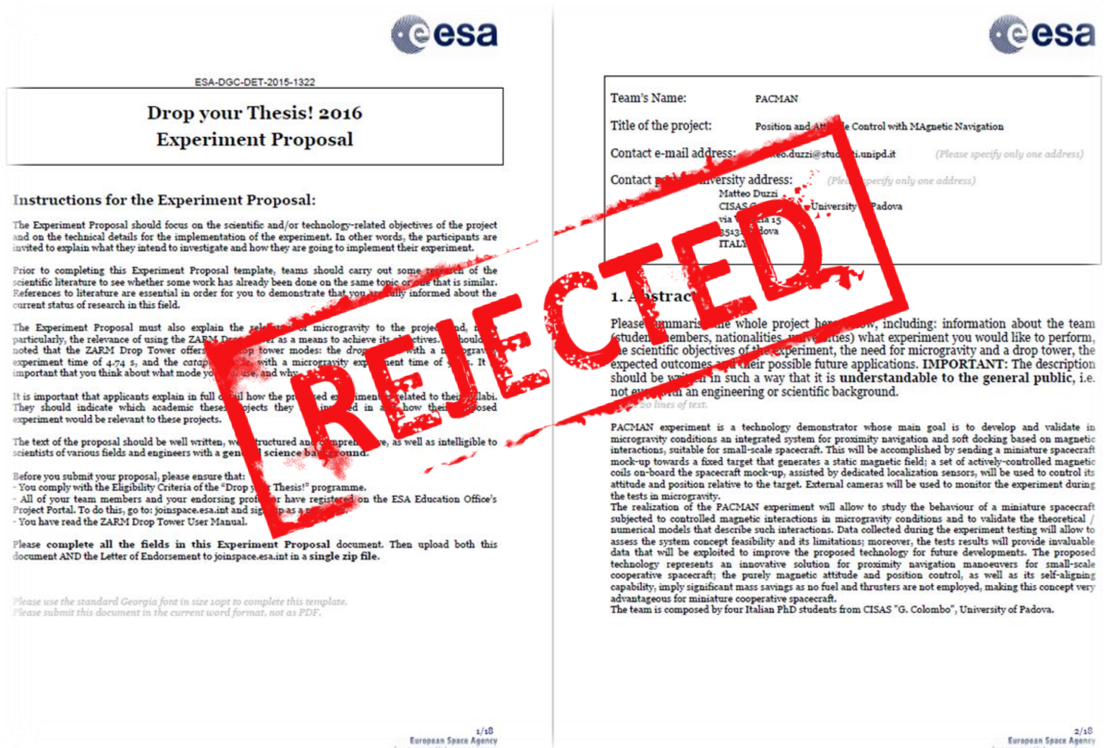
→ 1 month

Future works

Experimental Setup

ESA *Drop Your Thesis! 2016* programme - PACMAN

Perform scientific or technological research in microgravity conditions (10^{-6} g for about 5 to 10 seconds) using ZARM Drop tower



ESA-DGC-DET-2015-1322

Drop your Thesis! 2016
Experiment Proposal

Instructions for the Experiment Proposal:

The Experiment Proposal should focus on the scientific and/or technology-related objectives of the project and on the technical details for the implementation of the experiment. In other words, the participants are invited to explain what they intend to investigate and how they are going to implement their experiment.

Prior to completing this Experiment Proposal template, teams should carry out some [illegible] of the scientific literature to see whether some work has already been done on the same topic or [illegible] that is similar. References to literature are essential in order for you to demonstrate that you [illegible] informed about the current status of research in this field.

The Experiment Proposal must also explain the [illegible] microgravity to the proje[illegible] particularly, the relevance of using the ZA[illegible] as a means to achieve its [illegible] noted that the ZARM Drop Tower offers [illegible] tower modes: the *drop* [illegible] with a [illegible] experiment time of 4.74 s, and the *catap*[illegible] with a microgravity exp[illegible] time of [illegible]. It [illegible] important that you think about what mode yo[illegible] use, and why.

It is important that applicants explain in full [illegible] how the pr[illegible] ex[illegible] related to thei[illegible] They should indicate which academic these[illegible] they [illegible] in [illegible] how thei[illegible] experiment would be relevant to these projects.

The text of the proposal should be well written, we[illegible] structured an[illegible] as well as intelligible to scientists of various fields and engineers with a gen[illegible] science ba[illegible]

Before you submit your proposal, please ensure that:
- You comply with the Eligibility Criteria of the "Drop y[illegible] Thesis!" programme.
- All of your team members and your endorsing prof[illegible] have registered on the ESA Education Office's Project Portal. To do this, go to: joinspace.esa.int and sig[illegible]
- You have read the ZARM Drop Tower User Manual.

Please **complete all the fields in this Experiment Proposal** document. Then upload both this document AND the Letter of Endorsement to joinspace.esa.int in a **single zip file**.

Please use the standard Georgia font in size 10pt to complete this template.
Please submit this document in the current word format, not as PDF.

1/18
European Space Agency

Team's Name:	PACMAN
Title of the project:	Position and Att[illegible] Control with MAgnetic Navigation
Contact e-mail address:	[illegible]eo.duzzi@stud[illegible]ti.unipd.it *(Please specify only one address)*
Contact [illegible] university address:	*(Ple[illegible] specify only one address)* Matteo Duzzi, CISAS [illegible] University [illegible] Padova, via [illegible] 15, 3513[illegible] [illegible]dova, ITALY

1. A[illegible]strac[illegible]

Please [illegible] the whole project [illegible], including: information about the team (studen[illegible] members, nationalities, [illegible]) what experiment you would like to perform, [illegible]e scientific objectives of the experiment, the need for microgravity and a drop tower, the expected outcomes [illegible] their possible future applications. **IMPORTANT**: The description should be [illegible] in such a way that it is **understandable to the general public**, i.e. not e[illegible] an engineering or scientific background.

[illegible] 20 lines of text.

PACMAN experiment is a technology demonstrator whose main goal is to develop and validate in microgravity conditions an integrated system for proximity navigation and soft docking based on magnetic interactions, suitable for small-scale spacecraft. This will be accomplished by sending a miniature spacecraft mock-up towards a fixed target that generates a static magnetic field; a set of actively-controlled magnetic coils on-board the spacecraft mock-up, assisted by dedicated localization sensors, will be used to control its attitude and position relative to the target. External cameras will be used to monitor the experiment during the tests in microgravity.
The realization of the PACMAN experiment will allow to study the behaviour of a miniature spacecraft subjected to controlled magnetic interactions in microgravity conditions and to validate the theoretical / numerical models that describe such interactions. Data collected during the experiment testing will allow to assess the system concept feasibility and its limitations; moreover, the tests results will provide invaluable data that will be exploited to improve the proposed technology for future developments. The proposed technology represents an innovative solution for proximity navigation manoeuvers for small-scale cooperative spacecraft; the purely magnetic attitude and position control, as well as its self-aligning capability, imply significant mass savings as no fuel and thrusters are not employed, making this concept very advantageous for miniature cooperative spacecraft.
The team is composed by four Italian PhD students from CISAS "G. Colombo", University of Padova.

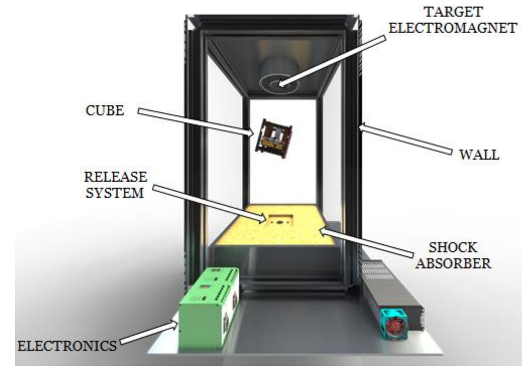
2/18
European Space Agency

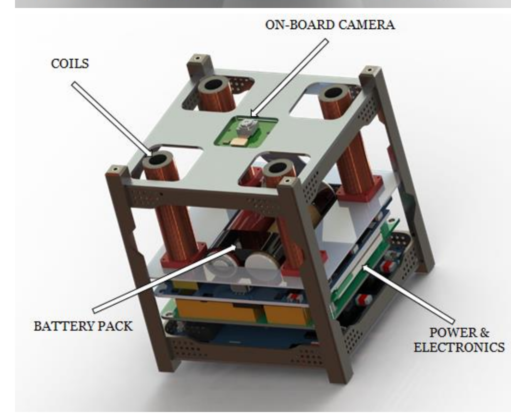
The design of the electromagnetic interfaces together with the experimental setup have been carried out during the proposal writing

Experimental Setup

ESA *Fly Your Thesis! 2017* programme - PACMAN Pre-Selection

Perform scientific or technological research in low-gravity conditions (10^{-3} g for about 10 to 20 seconds) using Airbus A310 Zero-G airplane. Each campaign consists of a series of three flights of 30 parabolas each.





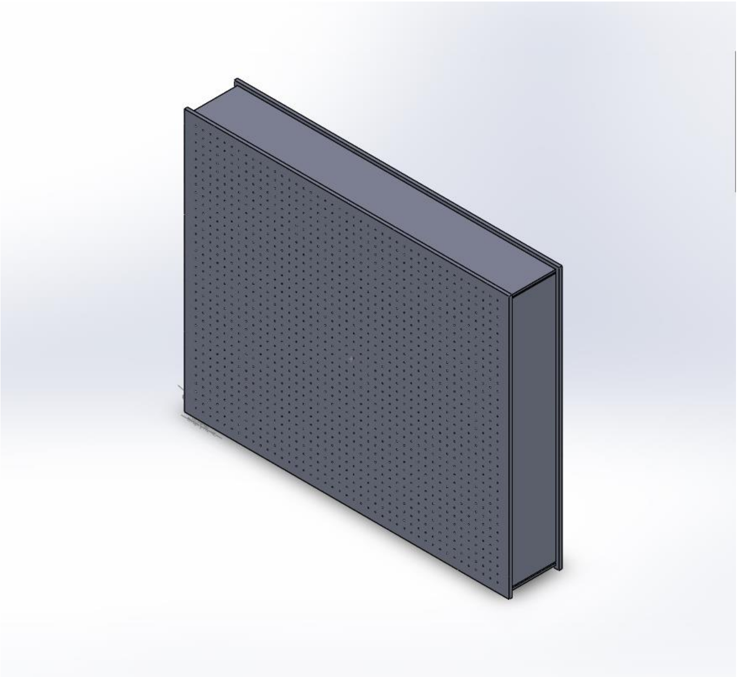
Experimental Setup

Low Friction Table

The experiment design, feasibility studies performed and all the work done to participate to ESA programmes are still effective and applicable for laboratory testing with minor changes

Features:

- Dimensions: 100x80 cm
- Holes diameter: 3 mm
- Holes distances: 2.5 cm
- Pressure: ~3 bar
- Hover load: ~5 kg



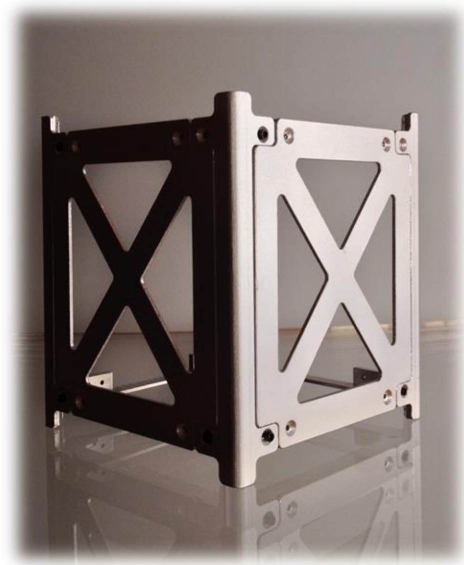
Status: still under development

End of the year (2016): "Nice 'n ready"

Activities connected to the research

OnOrbit Project

Preliminary studies for the development of a CubeSat



CONTENT

Work Done

- ✓ Electromagnetic interactions
  - ❑ Dipole model
  - ❑ Dipoles dynamics
- ✓ Tether
  - ❑ Dumbell model
  - ❑ Deployment dynamics
- ✓ TED simulations

} 5 months

- ✓ Experimental setup
  - ❑ ESA Drop Your Thesis programme: PACMAN
  - ❑ ESA Fly Your Thesis programme: PACMAN Pre-Selection
  - ❑ Low friction table
- ✓ Activities connected to the research
  - ❑ OnOrbit project

} 3 months

Current situation

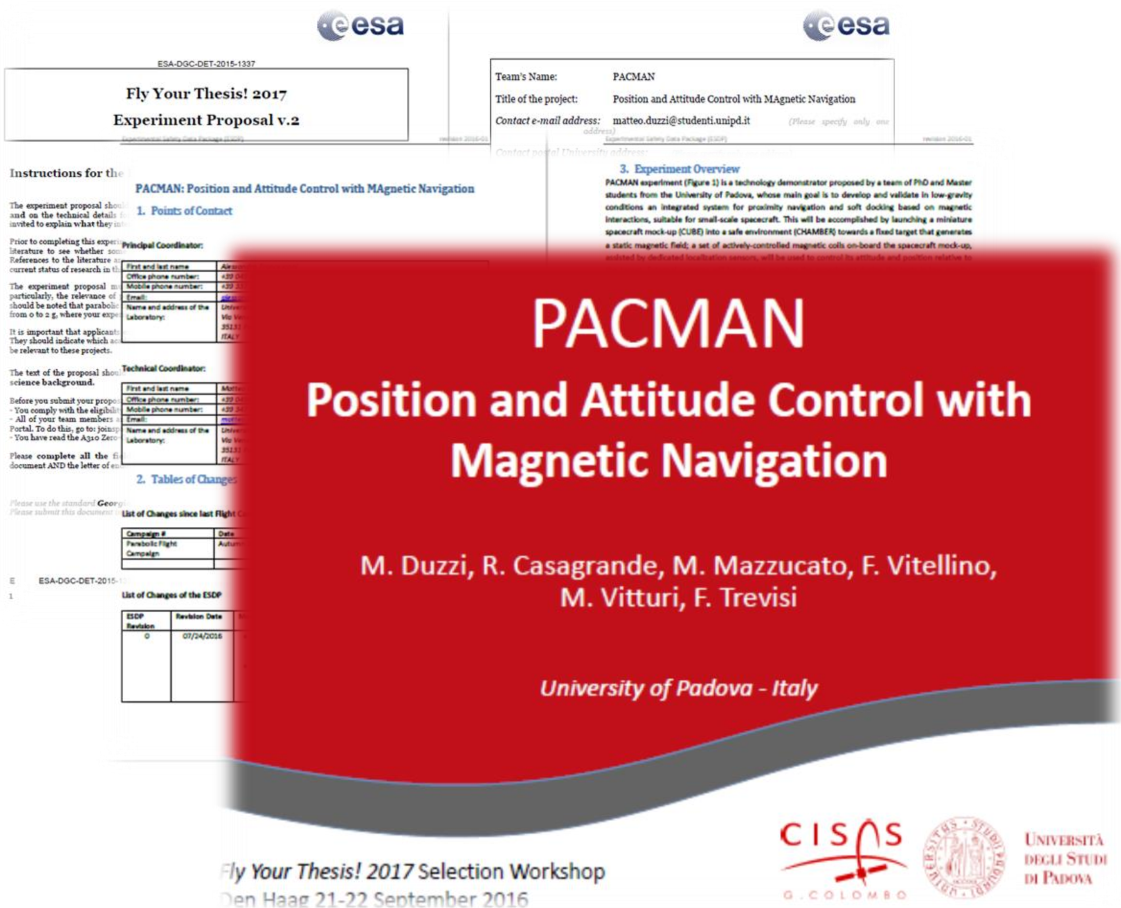
- ✓ ESA Fly Your Thesis programme → 1 month

Future works

CURRENT SITUATION

ESA *Fly Your Thesis! 2017* programme

PACMAN Selection Workshop



Last option

CORA
(Continuously Open Research Announcements)
ZARM Drop tower

↓

Backup solution

Low friction table

Conferences

- **4S Symposium – Small Satellite Systems and Services.** Malta, 30 May - 3 June 2016.
- **ESA Fly Your Thesis Selection Workshop.** Den Haag, 21-22 September 2016.
- **67th International Astronautical Congress.** Guadalajara, 26-30 September 2016.

Pubblications

- *SCRAT Experiment: a student experience.* **M. Duzzi**, L. Olivieri, A. Francesconi. In: 1st Symposium on Space Educational Activities. Padova, 9-11 December 2015.
- *Tether-aided spacecraft docking procedure.* **M. Duzzi**, L. Olivieri, A. Francesconi. In: 4S Symposium (Small Satellites, Systems & Services). La Valletta, 30 May – 03 June 2016, Malta.
- *Spacecraft joining using a tethered electromagnetic probe.* **M. Duzzi**, G. Grassi, L. Olivieri, A. Francesconi. In 67th International Astronautical Congress. Guadalajara, 26-30 September 2016.
- *Tethered docking systems: advances from FELDs Experiment.* D. Petrillo, M. Gaino, **M. Duzzi**, G. Grassi, A. Francesconi. In 67th International Astronautical Congress. Guadalajara, 26-30 September 2016.

- *Discontinuous mechanical problems studied with a peridynamics-based approach.* Mirco Zaccariotto, Giulia Sarego, Daniele Dipasquale, Arman Shojaei, Teo Mudric, **Matteo Duzzi**, Ugo Galvanetto. AIDAA2015.
- *Semi-androgynous multifunctional interface for expandable space structures.* Lorenzo Olivieri, Andrea Antonello, **Matteo Duzzi**, Francesco Sansone, Alessandro Francesconi. IAC2015.
- *Numerical simulations and experimental tests results on a smart control system for membrane structures.* Laura Bettiol, Francesco Branz, Andrea Carron, **Matteo Duzzi**, Alessandro Francesconi. IAC2015.
- *Tethered electromagnetic capture: a CubeSat mission concept.* Lorenzo Olivieri, Francesco Branz, **Matteo Duzzi**, Riccardo Mantellato, Francesco Sansone, Enrico C. Lorenzini, Alessandro Francesconi. IAC2015.

UNIVERSITÀ DEGLI STUDI DI PADOVA

CISAS G. COLOMBO

CURRENT SITUATION

Level				Activity description (WP title)	I year	II year	III year
Event				Presentation for approval of Research	▼		
1	**0**	**0**	**0**	**BACKGROUND & MOTIVATIONS**			
	1	0	0	State of the Art			
		1	0	Standard rendezvous manoeuvre			
		2	0	Standard docking manoeuvre			
		3	0	E-M formation flight			
	2	0	0	Objectives & Reasearch Statement			
		1	0	Definition of the E-M docking approach			
	3	0	0	Trade Off			
		1	0	Perspective applications			
			1	On-orbit servicing			
			2	On-orbit assembly			
2	**0**	**0**	**0**	**RENDEZVOUS & DOCKING MODELLING**			
	1	0	0	E-M Rendezvous & Docking Modelling			
Event				Admission to II year	▼		
		1	0	Models definition			
			1	E-M interfaces			
			2	Tether			
		2	0	Simulations			
			1	E-M probe dynamics			
			2	Tether dynamics			
			3	E-M docking manoeuvre			
Event				Admission to III year		▼	
3	**0**	**0**	**0**	**EXPERIMENT DESIGN & TESTING**			
	1	0	0	E-M Interfaces			
		1	0	Design of the E-M interfaces			
	2	0	0	Experimental Setup			
		1	0	Design of the low friction table			
	3	0	0	Testing in Relevant Environment			
		1	0	Application to ESA DYT!2016 programme (done)			
		2	0	Application to ESA FYT!2017 programme (in progress)			
		3	0	Application to ESA CORA programme (TBD)			
4	**0**	**0**	**0**	**THESIS**			
				EDUCATIONAL ACTIVITIES			

Future works

End of September 2016

1. Fly Your Thesis! 2017 programme
2. CORA

October – December 2016

1. Improve the code
    - (study tether retrieval)
    - (implement the Near Field model)
2. Conclude the experimental setup (low friction table)

January – September 2017

1. Testing
2. Write the Thesis
3. Write paper/articles
4. Period abroad?

THANK YOU FOR YOUR KIND ATTENTION!
ANY QUESTIONS?