CUBESAT TEAM OF POLITECNICO DI TORINO: PAST, PRESENT AND FUTURE PROJECTS

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ABSTRACT

The CubeSat Team is a student team of Politecnico di Torino involved in the design and development of small platforms for scientific space missions and for testing new technologies in orbit. The team was created in 2008 on the initiative of students and professors of the Aerospace Engineering course. More than 150 students got involved in the program since then. The CubeSat Team is coordinated by the Systems and Technologies for Aerospace Research team of the Mechanical and Aerospace Engineering Department, under the supervision of Professor Sabrina Corpino.
The objectives of the program are summarised in the following mission statement: "To educate aerospace-engineering students on systems development, management, and team work. To achieve insight in the development of scenarios and enabling technologies for future space missions"
In these years, the CubeSat Team reached great achievements, above all the launch of the e-st@r-I spacecraft, one of the two first Italian CubeSats in orbit. Students got involved in the design, development, and verification effort and participated actively in the integration and launch campaign. At the moment, two other CubeSats are being developed at the Systems and Technologies for Aerospace Research laboratory (STARLab): e-st@r-II, and 3-STAR, which are respectively part of the ESA "Fly Your Satellite!" and GEOID programs. The primary scientific payload of e-st@r-II is an active Attitude Determination and Control System for which innovative determination algorithms have been developed. The CubeSat successfully completed the environmental test campaign on June 2015 at ESA-ESTEC. 3-STAR is a 3U CubeSat that will take part in the GEOID constellation for the validation of the GENSO network through the HumSat communication payload. In addition, 3-STAR carries a remote sensing GNSS-based payload. This experiment will open the door to several applications, from Earth monitoring to civil protection warning services, and eventually military missions.
The team is also working on the definition of new mission concepts to define innovative solutions targeted to establish low-cost/fast-delivery space assets for science and exploration of the Solar system. The aim of these missions is to increase the scientific and technological knowledge with unprecedented measurements and by exploiting the potentialities of interplanetary CubeSats as distributed systems. At the present moment, two main destinations are considered: Mars and Near Earth Asteroids. For these studies, two important international collaborations have been established, with MIT and NASA's JPL.
All these activities will be described into the details in the paper.

1. Introduction

The CubeSat Team is a student team which deals with the design and development of space missions carried out by small platforms, in collaboration with other universities and research centers, international agencies and industry. The group consists of undergraduate and PhD students led by Prof. Sabrina Corpino and works in the Systems and Technologies for Aerospace Research Laboratory (STARLab), located inside the Department of Mechanical and Aerospace Engineering of Politecnico di Torino (DIMEAS). The core of the team consists of Aerospace Engineering students, but also students from different courses of study (e.g. Mechanical Engineering, Electronics and Telecommunications) are an important part of the team.
The Team is officially recognized as a student team of Politecnico di Torino. This gives the opportunity for students to be granted their participation in the team with credits, with which they can replace one of the exams of the study plan. Moreover, the Team receives financial support by the university through the committee "Fondi Progettualità Studentesca" (Funds for Students Projects), which basically reinvests part of the annual fees paid by students, by financing projects of the students themselves.
The Team has an official website (www.polito.it/cubesat-team) where is possible to find all the information on the projects, the collaborations and the team members. In addition, the outreach planning relies greatly on social networks (i.e. Facebook, facebook.com/CubeSatTeam, and Twitter, twitter.com/CubeSatTeam) to raise awareness of our research and to attract, at the same time, both new students and new sponsors.

2. Research activities

The CubeSat Team was created on 2008 with the objective of giving hands-on experience opportunities to university students, by establishing different research lines. Since the beginning, the Team focuses its activities on working on CubeSats missions and platforms, mainly as educational programs but also for technology demonstration and scientific purposes. Specifically, it conducts mission studies, design, development, integration and launch of CubeSats, which are a type of miniaturized and standardized satellite greatly appreciated worldwide, as demonstrated by the significant increase of platforms launched in recent years [1].

Programs developed by the Team have a common mission statement, which sums up the basic idea of research and education:

"To educate aerospace-engineering students on systems development, management, and team work. To achieve insight in the development of scenarios and enabling technologies for future space missions."

The hands-on-practice approach is considered a good mean to achieve our objectives as technical University, and this is the main reason why a structured permanent education and research program based on CubeSat has been established at Politecnico di Torino. The program is based on the idea that Universities shall take up the technological challenges issued by the scientific community and industries, in order to gain knowledge necessary for future space mission.

As Figure 1 illustrates, a space mission carried out by a University is driven first of all by the relevance that the mission has both for the research and the education purposes, being at the same time constrained by limited budget and resources.

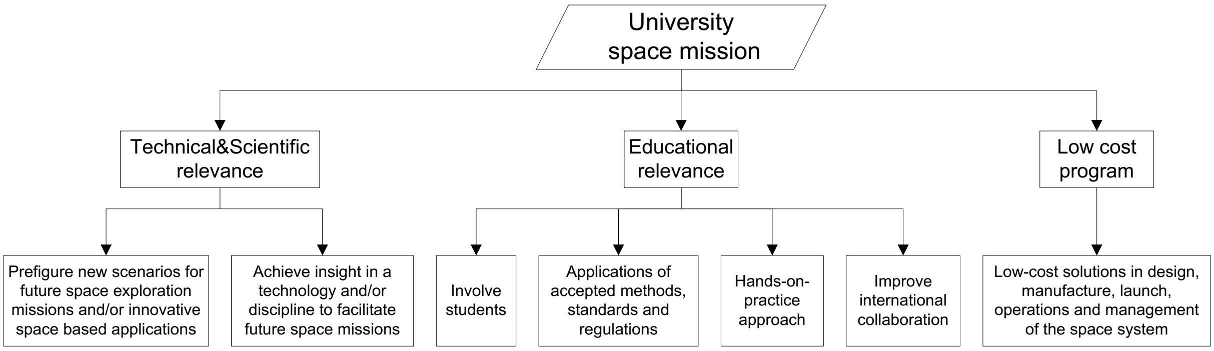

Figure 1: University space mission guidelines

The main program guidelines have been assumed as high level objectives and constraints for the research program. They can be listed as follows:

- WHAT/1: To inspire and prepare future space-professionals: students are the end users of the mission
- WHAT/2: To improve knowledge in space science and engineering: real world shall take advantages of our missions
- WHY: To meet stakeholders' needs. Stakeholders are: students & civil society, scientific community, industry
- HOW: To carry out a space program from the design to in-orbit operations, completely managed by students.

Since our research program has educational relevance, students must learn how to build a space mission from the very beginning throughout the project development, dealing with all the aspects related to a space program. The project is entirely carried out by the Team coordinated by the Team Leader, who is responsible for the whole program. The team is organized according to a defined work breakdown structure, which takes into account both technical and non-technical aspects. Students learn by practice how to:

- Design, manufacture, verify and test, and operate a space system
- Manage, control and document the development process according to current regulations and applicable standards (e.g. ECSS)
- Prepare technical documentation to report the project
- Team working and collaborate in an international multicultural environment
- Disseminate the results of the program
- Promote the program within the suitable stakeholders.

The educational purpose of the program is pursued at several levels:

- Undergraduate CubeSat program consists of class works developed during regular courses of the Aerospace Engineering Bachelor degree. Assignments are usually related to equipment-subsystem of the CubeSat. Undergraduate students also join the CubeSat Team for the preparation of

their final work, or for the mandatory internship. About 20 students participate in the activity every year
- Graduate students are involved in the CubeSat program during regular courses of the Master of Science in Aerospace Engineering and for the preparation of their final thesis. Master students works on the definition of the mission and of the system, as well as on the development and verification phases according to their talent and program schedule. Some of them join the CubeSat Team for 6 to 12 months to study in depth particular subjects and to develop their final work. Several students that have joined the team during the Bachelor degree then remained within the team until the completion of the Master of Science degree. About 40 students participate in the class work activity every year, and about 10% out of them remain in the team for the preparation of the thesis
- Postgraduate program. The CubeSat Team consists mainly of PhD students, who are usually the leaders of single units and coordinate the group of under-graduate and graduate students within the same unit. One PhD student is the System Engineer of the CubeSat project and coordinates all the technical activities. PhD students deal with CubeSat-related technology development and methodologies definition. At the moment, three PhD students are working on the CubeSat program full time.

2.1. Satellite programs

Currently, two CubeSat programs are being developed by the Team: e-st@r program, based on 1U platforms, and 3-STAR program, which instead aims at developing a 3U.

2.1.1. E-st@r

E-st@r program was born on 2008 in response to an initiative of the Education Office of the European Space Agency (ESA). The first platform developed within this program is e-st@r-I, a 1U CubeSat [2]. The project was selected among other ESA state members' universities to be launched on VEGA Maiden Flight as secondary payloads [3]. Finally, it was launched on February 2012 with other six platforms and it has been one of the first two Italian CubeSats to reach the space.
The payload was an active Attitude Determination and Control Subsystem (ADCS) aimed at demonstrating autonomous attitude control capabilities based on magnetic actuation [4].
The development of the first CubeSat led to achieving remarkable technical results:

- A platform for satellites CubeSat class was developed, tested on the ground and in orbit. This can accommodate different payloads and be adopted as the reference bus future projects. Many devices and components manufactured and tested precisely for e-st@r-I (e.g. ADCS board, magnetic torquers, antenna deployment system [5], etc.) could be easily integrated in next projects
- A mobile Ground Control Station (GCS) was built and it was very useful especially during the verification phase, system tests and as a backup of the main GCS during in-orbit operations
- Methodologies, design tools and verification procedures were developed and established, and they are still adopted in the current projects [6].

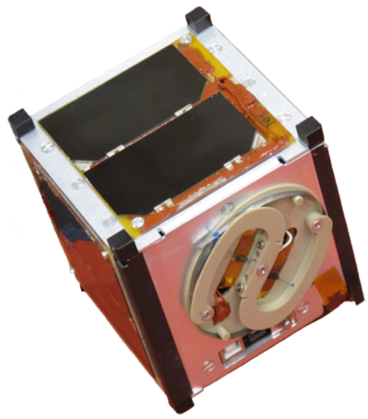

Figure 2: e-st@r-I CubeSat

Several lessons learned were collected during e-st@r-I design and AIV phases. However, the educational objectives were successfully achieved but the technical mission was not totally accomplished. In fact, even if the CubeSat successfully passed all verifications, in orbit it intermittently transmitted just only few days after the launch. Low battery voltage was targeted as the most possible reason for this failure.
Thanks to these results, lessons learned, the interest of students and the dedication of researchers and professors of the team, continuity was given to the work of the CubeSat Team with the launch of new initiatives: the project e-st@r-II and the program 3-star.
The development of e-st@r-II took advantage of the experience gained from its predecessor through the improvement of all subsystems, both hardware and software [7]. The development of the satellite started soon after the launch of the previous project, and then, in the first semester of 2013 it was selected for the ESA's "Fly Your Satellite!" (FYS!) initiative [8]. The payload is again the ADCS, with a major focus on a determination algorithm developed precisely for e-st@r-II. The aim is to demonstrate the capability of performing the estimation of the attitude even only with Earth Magnetic Field vector and angular velocities measurements. Secondary mission objectives are the test in orbit of COTS technology and in-house developed hardware (e.g. UHF communication system) and software (e.g. command and data handling software), which will demonstrate the students' skills and capabilities.

The "Fly Your Satellite!" program is an exciting initiative from the Education and Knowledge Management Office of ESA focused on CubeSat projects run by university students. The program is one of the several hands-on opportunities offered by ESA Education and provides experience of the full life-cycle of a space project. ESA provides the CubeSat teams with direct support from ESA technical specialists and access to state-of-the-art environmental test facilities. ESA will also procure a launch opportunity for selected CubeSat(s).
The satellite was selected to participate in Phase 1 ("Build your satellite!", with the review of the design conducted by ESA's experts) and Phase 2 ("Test your satellite!", with an environmental test campaign at ESA ESTEC, performed on May and June 2015 [9]), and it is waiting for gaining the "Ticket to Orbit!" (Phase 3) and to operate soon in space (Phase 4, "CubeSats in Space!").

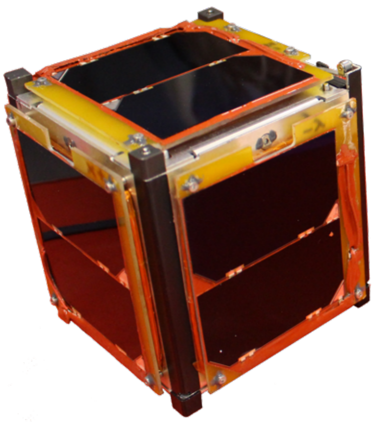

Figure 3: e-st@r-II CubeSat

2.1.2. 3-STAR

3-STAR program was born as a reaction to GEOID (GENSO Experimental Orbital Initial Demonstration) ESA Education Office in 2010. This initiative promotes:

- The creation of a constellation of CubeSat in Low Earth Orbit to validate the network of ground stations GENSO
- The development of the first set for the demonstration project HumSAT (Humanitarian SATellite) supported by European Space Agency and by the United Nations, which aims to improve the communication skills in developing countries and in countries affected by natural disasters or catastrophic events.

Within this program the CubeSat Team is designing and developing a 3U CubeSat form, 3-STAR [10], which is the evolution of the e-st@r platform. One of the payloads is developed in collaboration with students of the group Remote Sensing Department of Electronics and Telecommunications of the Politecnico di Torino, and so, from this point of view, the 3-STAR program is strongly multidisciplinary. The payload is P-GRESSION (Payload for GNSS Remote Sensing and Signal detectION) and the objective is to perform radio-occultation and reflectometry experiments. Currently, the program is in Phase B (Preliminary definition).

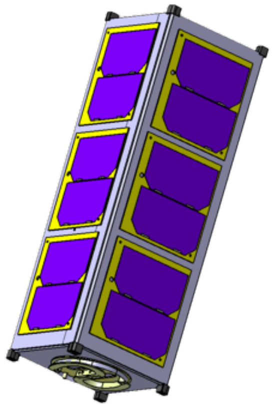

Figure 4: 3-STAR CubeSat (preliminary CAD model)

2.2. Mission design

One of the fields that our team is very involved in (similarly to satellite hardware integration and testing), is mission analysis and design. This is a wide category, and includes very different subjects:

- Tradespace exploration (for example Multi Attribute Utility Theory, a methodology with which great number of different possible designs are evaluated with respect to mission objectives and stakeholder needs)
- Detailed budget of the different subsystems (the "budgets" are a set of equations and formulas specific to the various subsystems that allow to define general and high level characteristics and that serve as basis to proceed with the detailed satellite design that is usually carried out in later stages)
- Analytical analysis such as astrodynamics (manoeuvres, trajectories and spaceflight) and architectures designs (telecommunications, distributed systems, and so on).

All these activities fall under the specified category of mission analysis and preliminary design. The students involved in these collaborations often have to deal with challenging problems, due to the fact that little is known of the mission and the system that will carry it out, and to the fact that the possible design choices are an enormous number.
Therefore, usually the students are assigned to a very specific task, often related to a reference mission that is used to allow the training of the new students.
The students principally are focusing their efforts in different fields: 1) Preliminary design 2) Coverage analysis 3) Mission architecture and concept 4) mission autonomy 5) Tradespace exploration (multi-attribute utility theory).

In these cases, the missions used as reference involve two technologies that are on the leading edge of the research effort in the small satellite field: distributed systems and interplanetary small satellites.

3. The role of the students and the opportunities offered to them

Many students have been involved in the programs of the CubeSat Team participating in every stage of the design (Figure 5), thus experiencing first-hand a real project and teamwork. The integration of components, the manufacturing operations of the devices, the mechanical tests, vibration, thermal vacuum, functional tests, simulations Hardware-In-The-Loop, have enabled dozens of students to express their ability in parallel the theoretical study, and to develop the System Engineer attitude, which will prove useful during the professional career. Indeed, many former members of the team are having the chance to work in companies with similar roles to those they had in the team, thus allowing them to exercise the skills acquired during their collaborations within the team. Some examples are shown in Tab. I.

Table I: Current jobs of some former members of the team

Former role in the team	Present job
System and AIV Engineer	Test Engineer @ Airbus DS
System Engineer	System Engineer @ Tyvak International
System Engineer	Innovation Engineer @ Heerema Marine Contractors
ADCS Engineer	GNC Engineer @ ELV
OBC engineer	Software Developer @ Magneti Marelli
OBC engineer	Data Handling Engineer @ Thales Alenia Space
OBC engineer	Software Engineer @ Airbus DS
GCS Engineer	Ground Systems Engineer @ SES Techcom

In several cases, the students finish off the work of months through the publication of scientific papers and internal reports, or theses (sometimes prepared within student exchange programs with other universities). In general, each student leaves the team with a Curriculum enriched by activities that are not commonly offered within the typical study plans. In addition, participation in workshops and meetings allowed them to get in touch with students from other countries, in international and multidisciplinary contexts (in Figure 6, many of the conferences and workshops attended by members of the Team are shown).

Over the past years more than 150 students have participated in the creation and development of CubeSat programs, including those have helped with project work and exercises, while being enrolled in the courses of the Bachelor and Master of Science. Some results:

- 25 thesis completed
- 20 publications in Proceedings of international conferences and workshops
- 3 manuscript accepted on international journals
- 22 works presented at events and conferences.
- 5 members involved in student exchange programs.

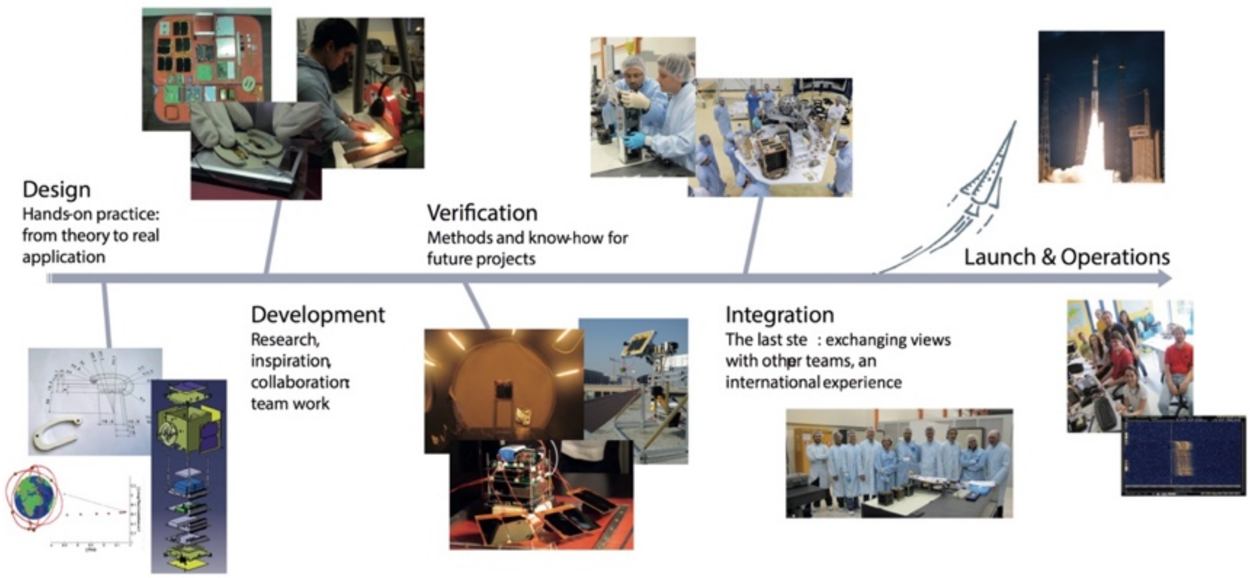

Figure 5: Phases of e-st@r missions in which the students have been involved

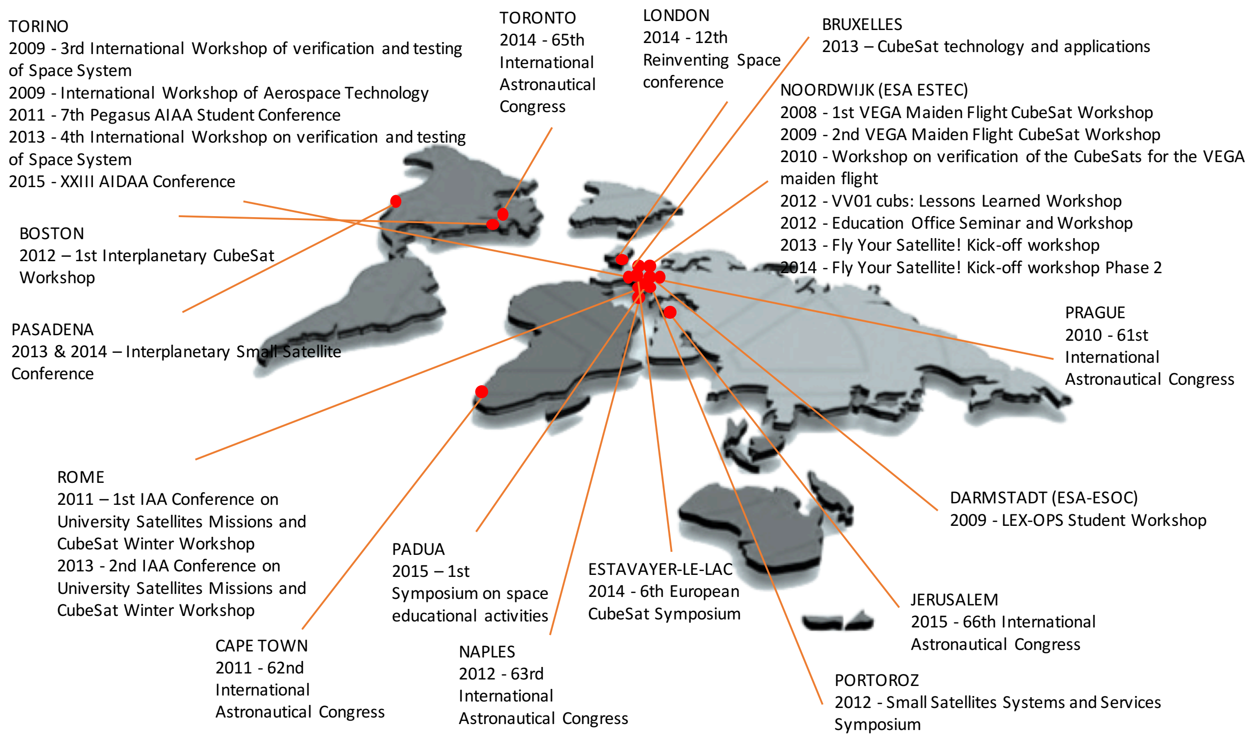

Figure 6: Conferences and workshops attended by members of the CubeSat Team

A very important event, both from the educational and technical point of view, is represented by the participation of the Team into the FYS! initiative.
The opportunity provided by ESA Education Office resulted to be very important for the students involved in all the phases of the initiative. Being in touch with the top experts in the field, first by email and teleconferences, and then side by side in the laboratories, is one of the best ways to acquire knowledge and to prove oneself in a professional context. Other key elements were the meetings and reviews between the Team and the ESA experts and managers, which represented a great outcome for all the students involved into the project. In fact, they have allowed to experience first-hand the project management related aspects.

4. Next projects and collaborations

The Team is always focused on the future, and of course the research activities are strongly influenced by the roadmaps established by space agencies.
The future research will investigate three principal branch of study, that are 1) innovative scientific missions, 2) optimal system design and 3) autonomous systems, relying on the relevant increase of the Technology Readiness Level of CubeSat-related technology.
As regards the scientific mission, the Team is looking at the new paradigm of interplanetary CubeSat [11] with two main destinations, Mars and Near Earth Asteroids (NEA). Both the missions take into account the possibilities offered by constellations and formations flying.
The objectives of a mission to Mars are to establish a low-cost/fast-delivery space asset to investigate specific phenomena that may affect the future human exploration of the planet and to provide the scientific community with unprecedented measurements to support the long term vision of human exploration of Mars. Three mission concepts for orbit, atmosphere and surface exploration were preliminary designed:

- Mars Orbital Environment Exploration (MOEX), which studies orbital particulate environment and dust climatology, focusing on micrometeoroids and dust rings by using CubeSat platforms. The MOEX mission concept is shown in Figure 7

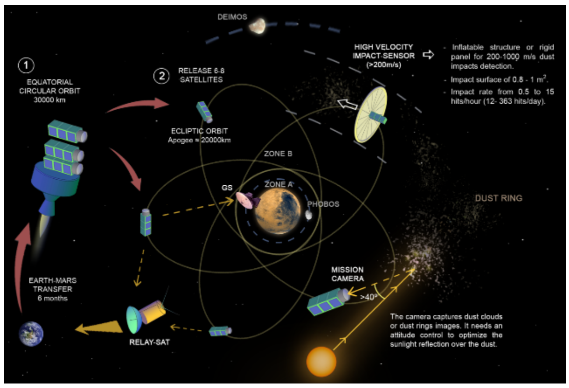

Figure 7: MOEX mission concept

- Mars Atmosphere Research with In situ Operations (MARIO), which investigates upper and lower atmosphere in order to characterize and study atmospheric features and processes of Martian atmosphere and its interaction with future human in situ missions. It consists of orbiters and swarm of CubeSats, and landers with deployable tethered balloons

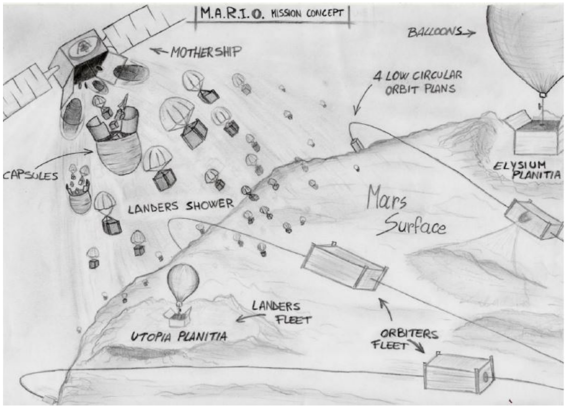

Figure 8 MARIO mission concept

- Spacecraft to Analyse Life-evidences Underneath Soil (SALUS). It searches for evidences on Martian (sub) surface that could represent hazard for human exploration, together with understanding if past/present life existed/exists on Mars. Space Penetrator System are the key elements of this mission, and they are based on CubeSat-sized technology

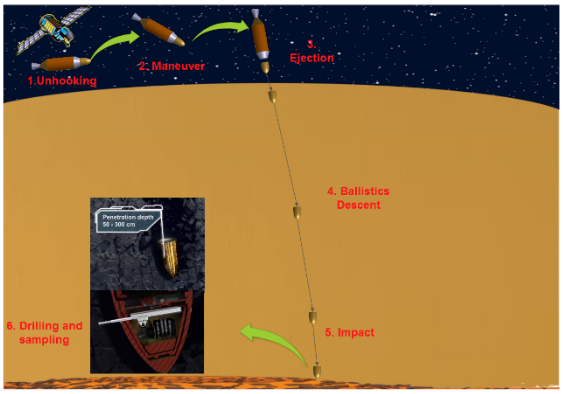

Figure 9 SALUS mission concept

NEA missions were identified by the International Space Exploration Coordination Group (which includes in practice the most important space agencies) as a potential pathway toward the driving goal of human exploration of Mars. The mission designed by the Team has the objective to deploy & operate a CubeSat-based space asset at a NEA, providing unprecedented measurements and data about the asteroid targeted to Solar System studies and knowledge-gap-filling activities, to the study of the consequences of an impact on an asteroid, and to the demonstration of key-technologies.

Going into details, the reference mission is a CubeSat mission to a binary asteroid, Didymos. The system will be object of a joint mission between ESA and NASA, that will launch each one spacecraft. The NASA one is going to impact the smaller component of the binary system, while ESA spacecraft will monitor the change in numerous parameters due to the impact of the other spacecraft.

Key objectives of the CubeSats under study are to enhance and support the science activities of the ESA spacecraft (measuring composition, type, properties and their changes post impact) and to explore and implement interesting and promising technologies that are currently at a lower technology readiness level (TRL).

A challenging aspect for the interplanetary mission is represented by the autonomy of the system. Indeed, the long distance from the Earth and the less available communication windows (if compared to LEO missions), entails the need for autonomous systems.

In the recent years, thanks to the increase of the know-how on machine-learning techniques and the advance of the computational capabilities of on-board processing, algorithms involving artificial intelligence (i.e. neural networks and fuzzy logics) have begun to spread even in the space applications. Nowadays, thanks to these reasons, the implementation of such techniques is becoming possible even on smaller platforms, such as CubeSats. In this context, the Team is also investigating the feasibility of a total autonomous system, by using Neural Networks, Fuzzy Logic and Genetic Algorithms.

For instance, thanks to the adaptability of these algorithms, it is possible to identify a failure and recover it not via active/passive hardware redundancy (as usually done) but only via software (e.g. by redistributing the control torques [12]).

The Team is also investigating the use of early design techniques in the development of CubeSat and related missions, focusing principally on the Concurrent Design (CD) methodology. This design methodology is relative young, in fact a first case study was provided by the CESAR mission assessment in March 1999, and is nowadays under study within the ESA and NASA's JPL facilities.

There are many definitions for Concurrent engineering but the ESA's preferred definition [13] best describes the Team idea too:

"Concurrent engineering is a systematic approach to integrated product development that emphasizes the response to customer expectations. It embodies team values of cooperation, trust and sharing in such a manner that decision making is by consensus, involving all perspectives in parallel, from the beginning of the product life-cycle."

The application of this new methodology within the Team will allow all the team members to learn from the others and to cooperate each other. One of the goals of our methodology is also to create a highly motivated and multidisciplinary team able to perform the design tasks in almost real time. Reaching these objectives is more difficult than it might first appear, but it can provide many benefits in terms of velocity and performance of the conceptual design and in the learning quality of the members.

Various partnerships are currently active and / or under development for the coming years. The most relevant are with Massachusetts Institute of Technology (MIT) and NASA Jet Propulsion Laboratory (JPL).

The collaboration with MIT was carried out during 2014 and it has been possible thanks to Intesa San Paolo, that through a public call, selected worthy projects and sponsored them. The people involved were two PhD students from Politecnico di Torino (that went to Boston) and three PhD students from MIT that were hosted in Torino. The subject of the collaboration was “CubeSat for space exploration: a new paradigm for planetary science mission”, and has been a fruitful joint effort between an engineering team (CubeSat Team) and a science one (EAPS department, Sara Seager's group). The research field was about distributed system on Mars, and the main task has been:

- To develop one or more mission concepts involving the use of CubeSat-like systems to perform distributed science on the planet
- To increase our knowledge about the environment and its dynamics, and gathering new data that would help the scientific community to prepare the way for human missions at Mars.

In this sense, the different background of the two participating teams was a positive and key aspect of the activity. MIT group provided the scientific knowledge necessary to characterize the initial structure of the mission. Indeed, helping to analyse into details the scientific problems related to it and to define with remarkable rigor the methodology used to explore the scientific part, was fundamental for the successful definition of the mission aspects. On the other side, CubeSat Team members were precious to provide the engineering knowledge that helped to define concept that were not only feasible, but also very appealing from the engineering research point.

The fundamental aspect of this collaboration was centred on the MEPAG (Mars Exploration Program Analysis Group) documents, which allowed us to select relevant scientific objectives that ensures actuality for our mission design effort. On this subject, after having defined the aforementioned characteristics, the teams defined the possible payloads, and from these the science traceability matrix for the mission, therefore exploring and tracing the link from the mission goals (and objectives) to the requirements (instrument, project, and mission). Analysis were carried out on various different disciplines, all involving early mission design. Going into details, the main focus of this second part has been performing concurrent design activities, allowing to define the mission concept with details compatible with a Phase A status, in a quick and efficient way. Moreover, on this subject, tradespace exploration (and in this Multi Attribute Utility Theory, MAUT) was addressed, and more detailed analysis on the mission were performed (mass, link, power and propulsion budgets, entry descent and landing).

The students at the end of the collaboration were extremely satisfied, and learned traversal skills thanks to the diverse teams that were participating. The professors involved were also a key part of this project, as they performed related educational activities during the periods as guest in the respective hosting universities.

As regards the collaboration between Politecnico di Torino and JPL/Caltech, it is being carried out during 2015, and involves two graduate students from the CubeSat Team that were hosted for months in Pasadena, California, in the renowned laboratory that is one of the excellence institutes in the space engineering and research (Earth Science and Interplanetary). The subjects of the collaboration are “Development of mission architecture concept study for a CubeSat asteroid mission” and “Design of the Thermal Control System of a CubeSat satellite”, and are all carried out under the JPL Visiting Student Research Program (JVSRP). The students are staying abroad for a period of 6 months each, and each student is having the chance to work on a similar and related field with respect to the one they were addressing when in Torino. This opportunity has been made possible because the JPL yearly selects a relatively small number of students and allows them to work as interns in their facilities, followed by mentors that add to the collaboration further aspects for the personal and professional growth of the students.

In addition to the environment being extremely interesting and motivating, because of all the space activities that are daily carried out in the laboratory, JPL puts a considerable effort in making the student stay as fruitful as possible. Guided tours of the laboratories and numerous conferences make the students very exposed to several state of the art practices.

Moreover, depending on the mentor that are assigned to, the students can be assigned to work also on secondary projects, enhancing the networking skills and allowing the students to interact more deeply with the current activities in the laboratory.

5. Conclusions

The CubeSat Team is a student team of Politecnico di Torino, which deals with the design and development of space missions carried out by small platforms. The group consists of a leading professor and undergraduate and PhD students, and works in the STARLab. The core of

the team consists of Aerospace Engineering students, but also students from different courses of study are an important part of the team.
The main activities of the Team are the two CubeSat programs, e-st@r and 3-STAR, and the missions design studies. To date, a 1U CubeSat (e-st@r-I) was launched within ESA's "CubeSats on VEGA Maiden Flight" initiative on 2012, and another 1U platform (e-st@r-II) is participating in ESA's "Fly Your Satellite!" initiative and after having successfully passed the environmental test campaign at ESTEC is now close to gain its ticket to orbit. In addition, a 3U CubeSat (3-STAR), is in the preliminary definition phase. Several scientific mission are being investigated, with two main destinations, that are Mars and Near Earth Asteroids.
The Team collaborates with other universities and research centres, international agencies and industry, and some other partnerships are being planned. At the moment, the most important collaborations are with MIT (the subject of the collaboration is "CubeSat for space exploration: a new paradigm for planetary science mission") and NASA's JPL (the subjects of the collaboration are "Development of mission architecture concept study for a CubeSat asteroid mission" and "Design of the Thermal Control System of a CubeSat satellite").

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