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ERMES: Experimental Rendezvous in Microgravity Environment Study

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Abstract

In the last decades the application of small satellites has increased substantially due to their wide use in technological, scientific and commercial domains. The coming of the "New Space Economy" has led to the opening of the market to small companies whose technological challenge is to develop miniaturized systems with high reliability and performance. Furthermore, the number of orbiting CubeSats has increased a lot, in fact it has more than tripled over the last few years, so they have become an interesting subject of study. Proximity navigation systems for autonomous small satellites are continuously examined, due to their effectiveness for several applications, e.g. related to on-orbit servicing.

In particular, this paper is concerned with the design and development of a test for an autonomous docking maneuver between CubeSats mock-ups to be performed on a parabolic flight in order to take advantage of a reduced-gravity environment. The main challenge of the proposed experiment lies in the dimension of the satellites involved, that implies the use of a miniaturized Guidance Navigation and Control system. The GNC system, based on a cold-gas propulsion subsystem and reaction wheels, will be used to perform proximity maneuvers in order to obtain the required alignment for the interfaces to dock. Concerning docking interfaces, two mechanical configurations are considered and will be tested, respectively a probe-drogue and an androgynous one, both developed by the University of Padova in order to be applied on miniaturized systems.

The development path includes tests in the laboratory for preliminary evaluations concerning the position and attitude control software and the performances of the miniaturized propulsive system, in view of a test in microgravity conditions. Such an experiment will be accomplished during a parabolic flight to reproduce the orbital behavior accurately and to get relevant data. Multiple flights are planned to allow the testing of different configurations separately and repeatedly.

This paper presents a detailed description of the experiment system, the results of the preliminary tests of the propulsive subsystem in the laboratory.

Keywords: CubeSats mock-ups, autonomous docking, miniaturized system, docking interfaces, parabolic flight.

1. Introduction

Recently, the access to space has become more economically affordable thanks to new technologies and advance manufacturing processes, so that small satellites have become a low cost solution to manufacture and to put in orbit due to their reduced dimensions and mass. Consequently, universities and industries have become more interested in their applications. Many private companies and organizations have started to invest in this field, studying new applications for miniaturized systems. In this perspective, thanks to the rise of this so called "New Space Economy", the number of miniaturized satellites, also called CubeSats, has incremented substantially. [1] In this scenario studies that investigates more reliable and efficient actuation systems, adaptable mechanical interfaces and software are of high interest.

In particular, this paper is concerned with the design and development of a test for an autonomous docking maneuver between CubeSat mock-ups. Space rendezvous are divided into three major phases: a first phase of fly-around that is used to insert the chaser in an orbit around the target, an approaching phase to reduce the distance and a final phase of proximity navigation that includes all the adjustment before the actual docking. This work is focused on the last phase, since proximity navigation maneuvers are notoriously difficult and risky, because mistakes during this phase could easily lead to mission failure. Normally the vast majority of docking maneuvers are carried out by astronauts, whose role is to check the proper progress of the operation, however small satellite-based missions cannot afford human monitoring, so they must rely on sensors and software to accomplish their tasks. Therefore, more efficient and reliable proximity navigation and control systems for autonomous small satellites are of great interest, due to their effectiveness for several applications in on-orbit missions. A further point of interest stands in the development of miniaturized mechanical docking interfaces suitable for the satellites involved in the missions, considering their reduced sizes.

2. Related Work

Autonomous space systems have always been an interesting topic in the scientific community because they allow particularly useful applications. The Automated Transfer Vehicle (ATV) [2] is one of the first example of an autonomous space system that carried out in multiple occasions rendezvous with the International Space Station (ISS). Autonomous Satellite Docking System (ASDS) [3] from Michigan Aerospace Corporation (MAC) had the goal to demonstrate the capability of an autonomous docking maneuvers between satellites on orbit, with a docking mechanism designed for soft-docking capability and tolerance to misalignment. More recently, Crew-2 Mission [4] performed an autonomous docking maneuver with the ISS without additional help needed from the robotic arm.

With the arrival of the "New Space Economy" and the resulting push towards small satellites based mission, the interest focused also on development of technologies for docking maneuvers between small satellites to study their effectiveness for applications related to on-orbit servicing. Some examples are:

- Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES) [5] aboard the International Space Station (ISS), consists of a series of miniaturized satellites developed by the Massachusetts Institute of Technology (MIT) used to test flight formations, rendezvous, autonomy algorithms in view of an implementation in future space architecture.
- CubeSat Proximity Operations Demonstration (CPOD) mission led by Tyvak Nano-Satellite Systems focused on a docking maneuver of two 3U CubeSats with a cold gas propulsion system for transnational maneuvers, image processing systems and testing of the docking mechanism on a frictionless table [6].

Other noteworthy experiments that investigated docking maneuvers for small satellites are: Autonomous Rendezvous Control And Docking Experiment (ARCADE) [7] and then Position and Attitude Control with Magnetic Navigation (PACMAN) [8] have examined the possibility of autonomous proximity navigation and docking, both implementing an electromagnetic based control system.

3. Ermes concept

ERMES stands for Experimental Rendezvous in Microgravity Environment Study: its main objective is the design of a test for an autonomous docking maneuver between CubeSats mock-ups to prove the feasibility of such difficult maneuver during space missions involving small satellites.

This objective will be reached by fulfilling the following low level goals:

- the development and testing of two system for Guidance Navigation and Control (GNC) based on cold gas propulsion and reaction wheels;
- the development and testing of a dedicated proximity navigation software;
- the performance comparison of two different mechanical docking interfaces;
- participation to the *ESA Education Fly Your Thesis! (FYT)* campaign to validate the system in a microgravity environment.

The experiment consists in an autonomous docking maneuver between two miniaturized satellites, both equipped with a GNC system and mechanical docking interfaces. The two mock-ups involved in the maneuver work in a target-chaser configuration where the target is passive and the chaser active. There is a substantial difference between the selected configuration in terms of actuators chosen for both CubeSats mock-ups. In fact, the chaser has a complete control on both its attitude and position thanks to a propulsive system based on carbon dioxide (CO2), while the target is equipped with reaction wheels that allows the control of only its attitude. That is because the target is supposed to work passively during the entire maneuver, contrasting unwanted disturbances and maintaining a fixed attitude, while the chaser locates and approaches it. The choice to implement a simpler system on the target than the one on the chaser is due to the necessity of an easier control; actually, the target has only the purpose of simplifying the approaching maneuver by just behaving passively. By contrast, if it moved uncontrollably depending on the disturbances, the chaser would have not only to perform the proximity navigation but also to keep into the account the change of the attitude of the target. Differently, the position and attitude control system of the chaser, based on cold-gas propulsion, is used to perform proximity navigation maneuvers in order to obtain the required alignment for the interfaces to dock. The configuration with one passive mock-up and the other one active was selected because it is the most likely situation on orbit.

Proximity navigation software will be developed in few steps, each phase is characterized by a development segment, and a test segment. The development part aim at implementing few necessary features needed to perform the test.
It will be used Robot Operating System and it will be implemented in C++. The operating unit will be a microprocessor like Arduino, and a more capable computer like a Raspberry Pi to perform heavy computations. The maneuver logic will be contained in the Raspberry Pi that acts as primary unit in the system.

The connection after a successful maneuver is obtained thanks to a miniaturized docking interface. In particular, the tests aim at drawing a comparison between two different kinds of docking mechanisms: a probe-drogue and an androgynous configuration described in Section 5.

The proposed experiment has been submitted to the *ESA Education Fly Your Thesis! (FYT) Programme* campaign [9], that allows the selected candidates to conduct their experiments in stable microgravity environment during a series of parabolic flights on the Airbus A310 Zero-G operated by NoveSpace. It consists of three flights with 31 parabolas each: as one parabola contains approximately $22s$ of microgravity, the teams experience over $10min$ of microgravity per flight and thus $30min$ in total. The call for proposals for this unique programme is annual and the opportunity to participate is granted to no more than four teams. The Parabolic Flight Campaign (PFC) lasts two weeks and takes place in Bordeaux. This particular flights are characterized by a parabolic trajectory relative to the center of Earth. When the aircraft is on its top the gravitational force is fully balanced causing a sensation of weightlessness. That is why, following this path, the aircraft and its payload are in free fall at certain moments. Although the experiment will take place in a parabolic flight in order to take advantage of the reduce-gravity environment and approximate the on-orbit one, preliminary simulations of the complete designed maneuver are conducted on a frictionless table in laboratory.

4. Guidance Navigation and Control system

This section focuses on the description of the actuation system of both target and chaser.

4.1 Cold gas system

An important development of ERMES concept is the miniaturized propulsion system based on cold gas because a lot of factors must be taken into account: total mass and volume occupied, mechanical and pneumatic complexity, power consumption and configuration of the selected thrusters. [10] The dimensioning and development of the configuration of the chaser starts from a general scheme that describes the basic functioning and points out the main component for the pneumatic subsystem. It is featured by a set of eight actively controlled thrusters capable of control of every degree of freedom during the three dimensional navigation. The selected configuration is powered by carbon dioxide stored in small tanks that are replaceable, so that in each test, the system would have the same initial mass. The thrust is generated through gas expansion in the nozzle, that is chosen to be simply convergent. The choice of a simple convergent nozzle, instead of a classic convergent-divergent one, is only a matter of avoiding supersonic flows because the experiment does not take place at zero pressure, so shock waves could occur.[11] The choice of a cold gas solution comes from the need of a simple but, at the same time, complete position and attitude control system, that ensures maneuverability, low power requirement, availability of the propellant and configuration versatility.

The circuit starts with a singular line from the tank to the pressure regulator and to follow a multiple four-way distributor. Then each line is further directed to a two-ways distributor. The final stretch of line is characterized by an ultra miniaturized 2-port normally closed solenoid valve and in the end by the simple convergent nozzle. All the tubing sections are with outer diameter of $4mm$ and thickness of $1mm$. In Fig. 1 is schematically represented the propulsive system.

In the conceptual design phase, several configurations are examined with a preliminary MATLAB code, that implements the general fluid dynamics equations and simulates the functioning of the propulsion system. In particular, the code focuses on computing Mach number, pressure and temperature at the distributors, at the electrovalves and at the nozzle exit and then evaluates mass flow rate and thrust. Therefore, the code is able to provide comparable data in sight of the testing phase. The pressure of the regulator at the beginning of the circuit is taken as the input parameter of the entire system, against which the rest of the variable can be studied. The code is based on five important hypothesis:

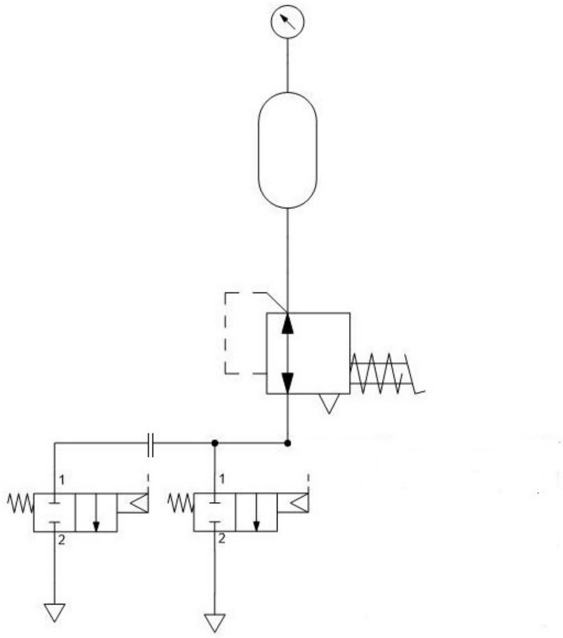

Fig. 1. Schematic of the ERMES cold gas propulsion system

- Expansion in the nozzle and Fanno flow are the only phenomena taken into account.
- The loss in pressure is concentrated at the distributors and defined as a percent of kinetic load.
- The loss in pressure for the electrovalves is negligible.
- As a safety factor, the stagnation pressure is considered as the value to set for the regulator.
- The dimensions of the system are inputs and depend on market availability

The results show that with a large expansion rate the fluid accelerates mostly in the nozzle, while in each section of the tubing the conditions are approximately unvaried because of the low Mach number. However, the interest lies mainly in the valuation of thrust and mass flow rate, shown in Fig. 2 and Fig. 3, because the former gives the level of authority of the system and the latter indirectly the quantity of mass of carbon dioxide needed for the maneuver. Two external pressure condition are considered, $1atm$ represents the laboratory while $0.8atm$ the condition on the parabolic flight. The two graphs represent only the conditions up to the adapted exit. After this condition is reached, although the pressure at the regulator increases, the fluid will still exit at a sonic condition but with a higher pressure. Moreover, since both thrust and mass flow are directly proportional to the pressure of stagnation, they will grow linearly.

Another important point to consider is the nozzle con-

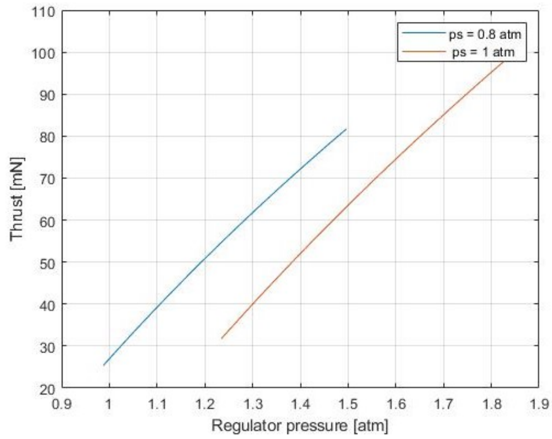

Fig. 2. Thrust per nozzle at external pressure of $1atm$ (lab) and $0.8atm$ (plane)

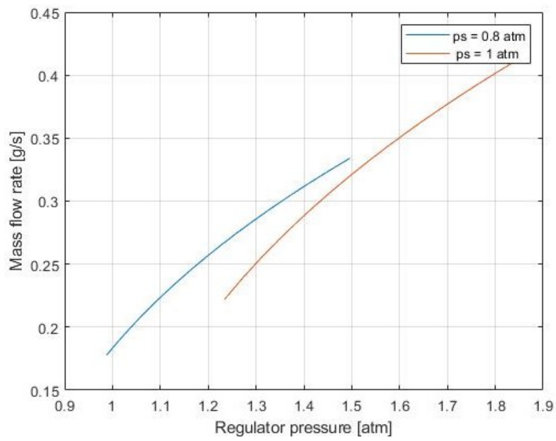

Fig. 3. Mass flow per nozzle at external pressure of $1atm$ (lab) and $0.8atm$ (plane)

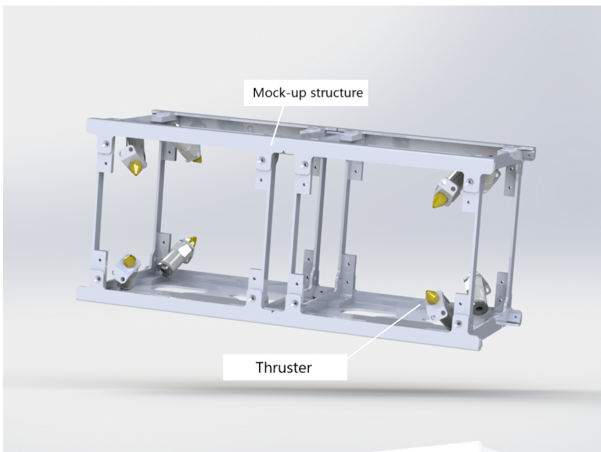

Fig. 4. Thrusters configuration

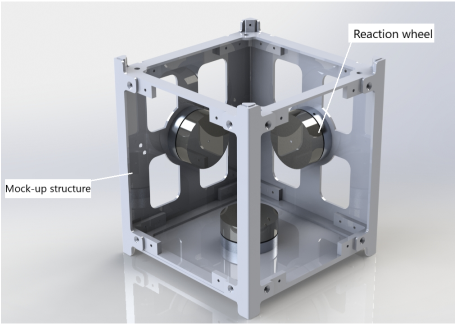

Fig. 5. Reaction Wheels configuration

figuration, in fact with the selected number of thrusters more solutions can be taken into account. First, it is needed to clarify that the configuration used during tests in the laboratory and the one chosen for the testing in the parabolic flight are the same, although fewer degrees of freedom have to be controlled. The configuration, shown in Fig. 4, consists of two groups of four thrusters placed on the opposite faces of the satellite. Secondly, every group is divided into two pairs so that for both faces, every pair of thrusters points toward the same point. This point must be different from the center of the face to allow the control of rotation around the direction of the normal axis of the face, assuming the center of mass at the center of the mock-up. Moreover, the nozzle must be tilted at a certain angle in respect of the plane of the face to allow the control of the translation in the direction of the normal axis of the face. This configuration allows controlling every degree of freedom during three-dimensional navigation.

4.2 Reaction wheels

Reaction wheels are moment exchange devices commonly used in many space missions for their versatility, simplicity and diversity. Their actuation entails a rotation of the satellite in reason of the conservation of angular momentum. They are widely implemented because of their authority, that allows not only to counter disturbances but also to control the attitude of the satellite.
As mentioned, the configuration for the target is based on three reaction wheels placed along three perpendicular axis. [12] In particular, during the experiment the target will work passively, mostly countering disturbances and correcting poor alignment in order to maintain fixed the axis of the docking interfaces in respect of the initial direction.

5. Miniature docking mechanism

An important choice for docking maneuvers is the docking mechanism: there are a lot of different configurations because different missions require different solutions in terms of dimensions, functionality and objectives. Every docking interface is characterized by the implementation of mechanisms whose main function is to provide a rigid connection between chaser and target. In particular, during the proposed experiment two miniaturized mechanical interfaces are tested, both specifically designed for CubeSats. The two configuration are based on two different basic mechanical principles:

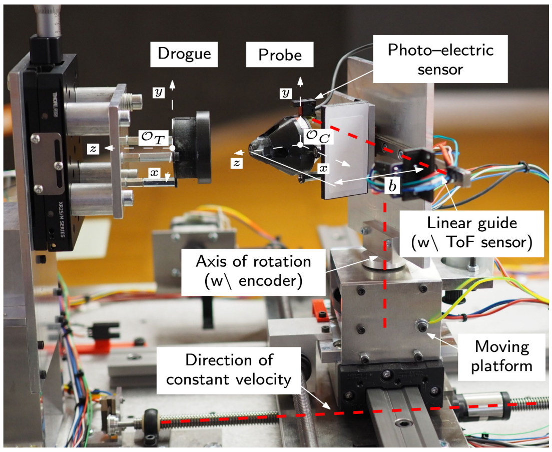

Fig. 6. Docking interfaces probe-drogue configuration [13]

- probe-drogue configuration, with an active probe and a passive drogue [13];
- androgynous configuration.

As it is shown in Fig. 6, in the probe-drogue configuration, the rigid connection is obtained from a physical insertion of the probe mounted on the chaser satellite into the complementary drogue mounted on the target. During the insertion phase, forced rotation and translation due to the complementary shapes of drogue and probe help to achieve the correct alignment. Finally, the last step consists of locking in the two satellites by a rotation of the tip of the probe that gets stuck inside the target structure. The rotation is achieved by a servo motor.
Whereas in the androgynous configuration, the rigid connection is obtained from an interlock between two external complementary interfacing structures, of which chaser and target are both equipped. The androgynous mechanism mounted on the target fit in the one of the chaser, then the rotation allows to lock the two CubeSats together.

Hence, although technically both systems provide a mechanical interlock, the kinematics and the dynamic process are characterized by different mechanical behaviors when it comes to forces and moments applied to the structures. ERMES proposes itself as a validation of the bench tests conducted on the mechanisms and aims to develop the experimental data to make a satisfactory comparison of the two interfaces.

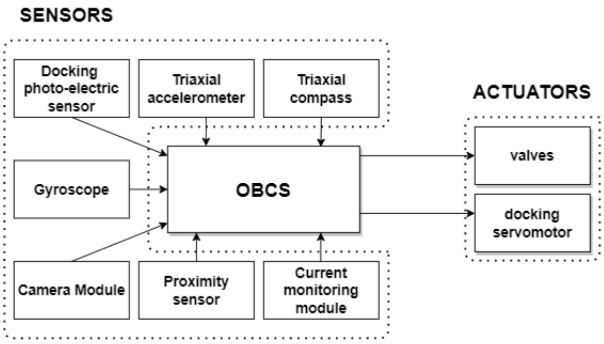

Fig. 7. Schematic Satellite Control System Architecture and Components

6. Satellite Control System Architecture and Components

ERMES will be equipped with an Onboard Computer System (OBCS), sensors, and actuators. The navigation actuators are valves that allow the Cold Gas System (described in Section 4) to activate under the OBCS commands.
There is a bunch of sensors necessary to calculate the correct trajectory for docking. These sensors are:

- triaxial accelerometer;
- gyroscope;
- triaxial magnetometer;
- proximity sensor.

In addition, a current monitoring module is implemented in such a way to check the battery pack status. Moreover, a low-res camera is equipped to find the target and check the position of the docking port during the locking maneuver.

The camera module is worth of note as it is used for the detection of a type of two-dimensional bar code. This is called AprilTag, and it will be fixed on the target CubeSat, so the principal CubeSat can detect and localize the objective.
AprilTag [14] is a visual fiducial system, useful for a wide variety of tasks including augmented reality, robotics, and camera calibration. AprilTags are implemented in the chose framework accordingly with Apriltag algorithm described in [15] and [16].
The algorithm that detects the AprilTag returns a quaternion that represent the position of the AprilTag in space in relation to the camera position (that is assumed as the origin). Further, processing like moving average could be useful to relieve possible errors.

6.1 Onboard Computer System

Onboard Computer System, or OBCS, is a part of the attitude and control system of the CubeSat, that is developed to control actuators and manage data from onboard sensors. [17]
OBCS is also the part of the system that computes other fundamental activities, among which: read signals data, recognize other CubeSat port direction and position, compute the path for reaching the secondary CubeSat in the current direction, send appropriate command toward the actuators and verify the maneuver performance.

In this experiment, the OBCS could be composed by two main nodes that interact with each other:

- the main unit used to perform the heaviest computations;
- the secondary unit used to send signals to the actuators and receive sensors data.

A Raspberry Pi [18] will be used as main unit to perform the experiment, it will be delivered with a clean Raspbian installation and the necessary framework to manipulate sensor data and calculate the path, other targeted tweaks could take place to achieve better reliability for the key computer's processes.

An Arduino-like platform is chosen for the secondary unit that permits a real-time process, in which it reads sensor data at an appropriate rate and sends the necessary commands to the actuators. The communication with the main unit consist of exchanging information between commands and sensor data; it is also important to highlight that there are not secondary tasks performed by the current unit. Which means it will be dedicated only to the described tasks. All complex calculations and the processing of the data will be performed by the other unit. This approach makes the code that will be in Arduino easily testable, because it has only basic and independent functions. One very clever objection is that approach increases the quantity of data transmitted on the connection, but in this case there are enough bandwidth to manage all sensors data and the commands received by the main unit. Further, test in this project will evaluate the real need of an Arduino platform, and choose between the higher complexity of 2 devices synchronized between each other, and the simplicity of using only the Raspberry Pi. The first method has the advantage that the Arduino node run with real time code, there are some techniques to run a real-time operating system in the Raspberry, and they will also be evaluated. The connection between the devices will be an USB cable. Each device has an UART (Universal Asynchronous Receiver-Transmitter) to manage the serial connection.

A Robot Framework-like system is used to implement the code necessary to manage all data and perform maneuvers, and ROS (Robot Operating System) is chosen to provide the services needed in this autonomous control scenario. Robot Operating System (ROS) is an open source middleware suited for robotic systems. It could

be seen as a collection of software frameworks that are related to the robotic environment, and it provides important features, which are hardware abstraction and low-level device control. ROS processes are represented by nodes, each one dedicated to one particular task. All nodes can communicate with each other if they need.
ROS is used because it's an open source project. It has a lot of useful features for this project, like April-Tag detection according to the last robust algorithm described in [15], it implements also some techniques for localization (like the package described in [19]). It also provides a lot of methods for this kind of project, like the transformation methods to change the reference on quaternions. It is characteristic structure composed by various node connected to each other is easy to understand. The connections between nodes follow the flow of data, which makes it elementary to understand the system as a whole.

In this project, the Arduino will implement a ROS Publisher to communicate sensors data, and a ROS Service to provide access to the control of the valves and the docking port. On the other hand, the main program will be hosted by the Raspberry. Note that in the case that the Arduino will be discarded as a viable solution, the ROS Service and the Publisher will be hosted by the raspberry. In this case, it could be a good idea to provide a priority to these processes.

7. Experimental Plan

The experimental plan consists of a series of steps that lead to the parabolic flight test execution. It can be divided in three major phases.

The first phase concerns with the validation of the physical model used to describe the pneumatic subsystem. In particular, it consists in a preliminary assembly of the pneumatic system to confirm the mechanical connection of the components, and it also deals with tests to confirm the values of all the fluid dynamic variable of the system. The tests are also designed to evaluate potential critical points for losses in pressure.

The second phase is the biggest and most demanding one. Firstly, it deals with the tests about the correct functioning of all subsystems, considering each subsystem individually and also as a whole. Moreover, it addresses the development of the system architecture, software coding and testing. Proximity navigation software should be developed and tested in few steps: initially, one satellite is configured to perform only forward and backward maneuver. The aim goal is to develop a system capable to perform basic maneuver precisely, so it is important to master the capabilities of electrovalves. Then a series of localization test would be performed, the satellite should be capable to detect the objective, which should be signalized via AprilTag or a LED scheme. The localization would use some other sensor to augment the situation awareness. The satellites should be capable to compensate some sensors errors. Some filters would be needed, like a Kalman Filter or a Particle Filter [20] adapted for the situation.
Then the local navigation system should be tested in a frictionless table and with three degrees of freedom: the CubeSat mock-up must be capable to move in the table maintaining awareness of its position. Finally, a series of complete maneuver test with 3 degrees of freedom should be performed to validate the approach. In these tests, the target should stay firm in position, while the chaser execute the maneuver. There are multiple steps in this experiment: initially the chaser navigates to the static one, then it would try to perform a docking maneuver with minimum vibration.
Each test phase is accomplished with the implementation of the necessary code. Before the real experiment, some Unit Tests must be done.

Finally, the last phase is characterized by the tests on the parabolic flight thanks to the *Fly Your Thesys! Programme* campaign, in particular, this phase deals with the data collection and study. It ends with a report writing about the experiment to submit to ESA.

Therefore, the experimental plan can be summed up as follows:

- Preliminary assembly of the propulsive system to confirm the mechanical connection of the components of the pneumatic subsystem and evaluate potential critical points for losses in pressure.
- Validation of the results from the MATLAB code about pressure, thrust and mass flow.
- Integration, calibration and testing of the sensors.
- Integration and testing of the electrical circuit dedicated to the control of the electrovalves.
- Integration and testing of the camera module for the Apriltag based visual recognition system.
- Validate the Apriltag approach and test the situation awareness of the system while it will be moved by with fixed and known translation and/or rotation.
- Validation, calibration and testing of the propulsive subsystem for movement and rotation control of the chaser.
- Validation, calibration and testing of the reaction wheels needed for target's attitude control.
- Development and testing of the software drivers necessary to control electrovalves and perform basic maneuvers in 1DoF.
- Perform basic maneuvers on frictionless table (3DoF).
- Check if the CubeSat mock-up is capable to maintain the position estimation error low enough to perform such maneuvers.

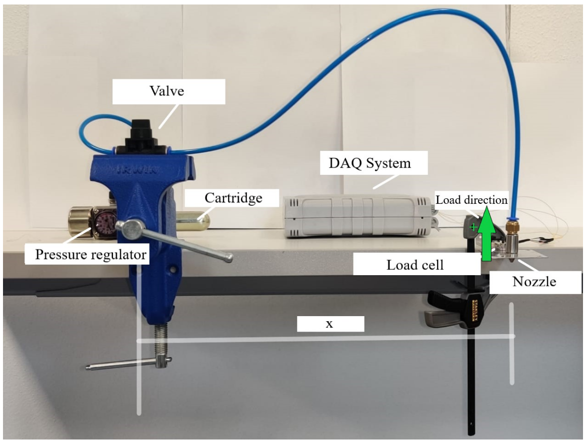

Fig. 8. Experimental configuration

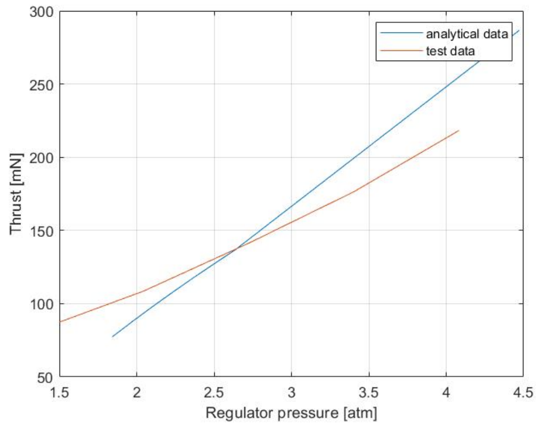

Fig. 9. Operative range of cold gas system from bench tests and analytical predictions

- Testing of a simplified two-dimensional maneuver, taking into account the GNC control systems of both target and chaser, and valuation of the alignment compared to the required one.
- Testing of both mechanical docking interfaces.
- Testing the final approach and the docking lock between the two satellites.
- Simulation of a complete two-dimensional docking maneuver on a frictionless table.

Currently, only the first steps have been performed. The preliminary experiment, designed to confirm the correlation between pressure and thrust, consists of a structure that supports a single nozzle and is connected to a load cell. The nozzle is connected to a simpler pneumatic system, composed of a pressure regulator and a mechanic valve, to control manually the flow. The output of the experiment system is the voltage of the Wheatstone bridge of the load cell. The first step is the calibration of the load cell, that has been conducted by varying gradually the mass applied to the structure that supports the nozzle.

Similarly, the data about the thrust are collected by varying the pressure at the regulator. In particular the selected value were 1.4, 2.0, 2.7, 3.4 and $4.0atm$, because they represent possible operating value for the propulsive system since they provide the $100mN$ $(10g)$ target value for thrust. This value has been selected because it is high enough to perform the tests on the frictionless table, but also because it permits to have low working pressure in the system, that indirectly implies the possibility to use smaller and simpler components. Therefore, comparing the data collected with different pressure inputs to the one of the calibration, it can be estimated the thrust in grams as shown in TABLE. 1.

The trend of the relation between variability of the pressure and thrust is presented in Fig. 9.

Table 1. Thrust in grams in respect of each pressure setup value

Pressure [atm]	**Thrust** [g]
1.4	8.2
2.0	10.8
2.7	14.1
3.4	17.6
4.0	21.8

8. Concluding Remarks

In conclusion, ERMES aims to prove the feasibility of autonomous space rendezvous with miniaturized systems, investigating not only structures and components involved but also architectures and software development approaches. Moreover, it represents a starting point for a more complex and detailed analysis of the versatility and potential of fully automatized space missions.

This paper presented the preliminary design of the subsystems, with special attention to their technical specifications. The project is still in an early stage, so although evaluations have been conducted, especially about the functioning of the components, much remains to be studied. In particular, the realization of the pneumatic system requires a complete knowledge of the fluid dynamic behavior, but in order to have validity of the analytical data more test must be conducted. From the first bench tests of the cold gas circuit emerges a good correlation between pressure and thrust, and the same order of magnitude of that estimated.

Regarding the maneuver, an optimal architecture of the satellite control system is required, so the development has to focus on the control of the thrusters more than their performances. This task represents the most demanding development of ERMES concept and the main focus of the next steps of the design. As mentioned, the current interest lies in the simulations on the frictionless table of a simplified system, so that the critical points can be evaluated in view of the final test in microgravity environment on the parabolic flight, where the potential of the attitude and position control system can be fully examined.

References

[1] Joseph Pelton. “The New Gold Rush”. In: vol. 1. Nov. 2017, pp. 159–176.

[2] P Amadieu and JY Heloret. “The automated transfer vehicle”. In: *Air & Space Europe* 1.1 (1999), pp. 76–80.

[3] Jane Pavlich et al. “Autonomous satellite docking system”. In: (2001).

[4] SpaceX. *Crew-2 Mission*. URL: *https://www.spacex.com/updates/crew-2-mission/index.html* (accessed 2021-09-20).

[5] A. Fejzic, S. Nolet, and D.W. Miller. “Results of SPHERES microgravity autonomous docking experiments in the presence of anomalies”. In: 8 (Jan. 2008), pp. 4878–4890.

[6] John Bowen et al. “CubeSat Proximity Operations Demonstration (CPOD) mission update”. In: *2015 IEEE Aerospace Conference*. 2015, pp. 1–8.

[7] Marco Barbetta et al. “Arcade experiment on board bexus 13 and 17: design, integration and flight of a technology test platform within a student balloon programme”. In: Dec. 2015.

[8] Matteo Duzzi et al. “Electromagnetic position and attitude control for pacman experiment.” In: May 2017.

[9] ESA. *ESA Education Fly Your Thesis! (FYT) Programme*. URL: *https://www.esa.int/Education/Fly_Your_Thesis/About_Fly_Your_Thesis* (accessed 2021-09-27).

[10] Ravi Ranjan et al. “Cold gas micro propulsion development for satellite application”. In: *Energy Procedia* 143 (Dec. 2017). Leveraging Energy Technologies and Policy Options for Low Carbon Cities, pp. 754–761.

[11] B.P. Madhu, G. Mahendramani, and K. Bhaskar. “Numerical analysis on flow properties in convergent – Divergent nozzle for different divergence angle”. In: *Materials Today: Proceedings* 45 (Oct. 2020). 4th International Conference on Advanced Research in Mechanical, Materials and Manufacturing Engineering-2020, pp. 207–215.

[12] Zuliana Ismail and Renuganth Varatharajoo. “A study of reaction wheel configurations for a 3-axis satellite attitude control”. In: *Advances in Space Research* 45.6 (Nov. 2009), pp. 750–759.

[13] Francesco Branz et al. “Miniature docking mechanism for CubeSats”. In: *Acta Astronautica* 176 (June 2020), pp. 510–519.

[14] APRIL Robotics Laboratory. *AprilTag*. URL: *https://april.eecs.umich.edu/software/apriltag.html* (accessed 2021-09-27).

[15] John Wang and Edwin Olson. “AprilTag 2: Efficient and robust fiducial detection”. In: *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, Oct. 2016, pp. 4193–4198.

[16] Danylo Malyuta. “Guidance, Navigation, Control and Mission Logic for Quadrotor Full-cycle Autonomy”. Master thesis. 4800 Oak Grove Drive, Pasadena, CA 91109, USA: Jet Propulsion Laboratory, Dec. 2017.

[17] ESA. *Onboard Computers*. URL: *https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Onboard_Computers_and_Data_Handling/Onboard_Computers* (accessed 2021-09-27).

[18] RASPBERRY PI FOUNDATION. *Raspberry Project*. URL: *https://www.raspberrypi.org/* (accessed 2021-09-27).

[19] Thomas Moore and Daniel Stouch. “A Generalized Extended Kalman Filter Implementation for the Robot Operating System”. In: *Intelligent Autonomous Systems 13*. Ed. by Emanuele Menegatti et al. Cham: Springer International Publishing, 2016, pp. 335–348.

[20] Pierre Del Moral. “Nonlinear filtering: Interacting particle resolution”. In: *Comptes Rendus de l’Académie des Sciences - Series I - Mathematics* 325.6 (1997), pp. 653–658.