ERMES: Design and preliminary simulations for an autonomous docking manoeuvre

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Abstract

In the last decades, small satellites have played an important role in space missions. Due to their reduced dimension and costs, they became affordable to smaller companies and research laboratories to conduct scientific experiments and technological demonstrations in space. In addition, the number of these satellites has considerably increased due to their wide use in technological, scientific and commercial domains. In this scenario, autonomous architectures, as well as miniaturized mechanical subsystems for small satellites, are continuously investigated.

Experimental Rendezvous in Microgravity Environment Study (ERMES) is a student project that focuses on the simulation of an autonomous docking manoeuvres between two CubeSats mock-ups equipped with miniaturized Guidance Navigation and Control systems and mechanical docking interfaces. ERMES aims to integrate different subsystems for autonomous docking, to increase the Technology Readiness Level and to study possible applications for in-orbit servicing. This paper deals with the design and development of the tests for autonomous docking manoeuvres between two CubeSats mock-ups to be performed in a reduced-gravity environment during a parabolic flight. A Target-Chaser configuration has been selected, where the Chaser is fully active and the Target is cooperative. The Chaser is equipped with a miniaturized cold gas propulsion system with eight thrusters to control its attitude and position; in contrast, the Target has a set of three reaction wheels to control only its attitude. The tested miniaturized mechanical docking interfaces employs a probe-drogue configuration. The most demanding aspect of the development phase will be the dedicated software for the proximity navigation. The reduced-gravity conditions will be achieved during a campaign of parabolic flights thanks to the participation to the European Space Agency “Fly Your Thesis!” programme 2022.

Keywords

Autonomous docking, CubeSats mock-ups, miniaturized systems, parabolic flight, proximity navigation software.

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Nomenclature

p_{sonic}	*Sonic pressure*
p_{total}	*Total pressure*
γ	*Heat capacity ratio of CO_2*
T	*Thrust*
A_{exit}	*Exit Area*

Acronyms/Abbreviations

EKF	*Extended Kalman Filter*
GNC	*Guidance Navigation and Control system*
IMU	*Inertial Measurement Unit*
PWM	*Pulse Width Modulation*
ROS	*Robot Operating System*

1. Introduction

In the last decades, nano and micro class satellites have revolutionized the space industry making the orbital environment accessible to an increasing number of entities, such as industries, research centres or universities, thanks to their manufacturing simplicity and reduce cost and mass. This new opportunity led to a spike of interest towards studies that investigates more reliable and efficient actuation systems, adaptable miniaturized interfaces and software for autonomous satellites.

This paper focuses on autonomous docking manoeuvres between CubeSat mock-ups to be performed in a reduced-gravity environment. Docking manoeuvres can be divided into three major phases: the first phase of fly-around needed to insert the spacecraft in an orbit around the target, an approaching phase to reach it and, finally, a phase of proximity navigation that ends with the actual docking. ERMES interest lies mostly on the last phase since proximity navigation manoeuvres are notoriously difficult and troublesome because mistakes during this phase could easily lead to mission failure. Generally, most docking manoeuvres are not fully automatized and require an astronaut to check the proper progress of the operation, however small satellite-based missions cannot afford human monitoring. Hence, they usually rely almost entirely on sensors and navigations software to properly manoeuvre autonomously. Therefore, efficient navigation and control software, as well as miniaturized subsystems for autonomous small satellites are of great interest.

2. Background

Due to the interest in this kind of application, few space demonstrations of autonomous docking manoeuvres have been performed. For example the Automated Transfer Vehicle (ATV [1]) carried out on multiple occasions rendezvous with the International Space Station (ISS); more recently, the Crew-2 Mission [2] by NASA and SpaceX performed an autonomous docking manoeuvre with the ISS. Regarding small satellites studies it can be cited: Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES [3]) and Astrobee [4] aboard the ISS, consisting of a series of miniaturized satellites used to test flight formations, rendezvous and autonomy algorithms; the proposed CubeSat Proximity Operations Demonstration (CPOD [5]) mission, led by Tyvak Nano-Satellite Systems, that focused on a docking manoeuvre of two 3U CubeSats.

Finally, the University of Padova has a solid heritage on autonomous docking manoeuvres studies: the Flexible Electromagnetic Leash Docking system (FELDs [6]) studied an electromagnetic soft docking technology; Autonomous Rendezvous Control And Docking Experiment - Reflight 2 (ARCADE-R2 [7]) correctly performed three release operations and two docking procedures between 2-DOF vehicles; the Position and Attitude Control with Magnetic Navigation (PACMAN [8]) investigated the possibility of performing magnetic proximity navigation and attitude control for soft docking manoeuvre.

3. ESA Fly Your Thesis! programme

The *Fly Your Thesis! programme* is an opportunity granted by the European Space Agency's (ESA) Educational Office [9] to groups of university students from all over Europe, to conduct their experiments or technological demonstrations in controlled low-gravity conditions. These conditions are achieved on board of an Airbus A310 Zero-G, operated by Novespace, by performing a parabolic flight. This peculiar trajectory causes a drop of gravity level within the cabin nearing weightlessness that lasts for approximately 22 seconds per parabola. The campaign consists of a series of 3 flights of 30 parabolas each and takes place in Bordeaux.

4. ERMES concept

In this frame, the ERMES experiment aims to design and develop a test for an autonomous docking manoeuvre between two free-flying CubeSat mock-ups equipped with Guidance Navigation and Control (GNC) systems and miniaturized mechanical docking interfaces. This experiment will be performed on a parabolic flight since it has been selected for the ESA *Fly Your Thesis! programme* 2022.

In general, the ERMES experiment aims to prove the feasibility and versatility of autonomous docking manoeuvres between small satellites in view of future space applications and services, including large structures assembly, flight formations management and active space debris removal. Moreover, ERMES collects the heritage of previous projects of the University of Padova on autonomous systems for docking manoeuvre in order to increase even more the technology readiness level. Therefore, it presents itself as a further step towards a more complete on-orbit technological demonstration.

The two mock-ups involved in the manoeuvre (Fig.1) work in a Target-Chaser configuration, in which the Chaser actively performs the manoeuvre to reach the Target, that, in the meanwhile, acts cooperatively by contrasting unwanted attitude disturbances. Moreover, the manoeuvre will be performed autonomously but the mock-ups. The mock-ups will be released by a Release Structure composed of a holding mechanism to support the mock-ups prior to the start of the experiment and a slider to accelerate the Chaser towards the Target.

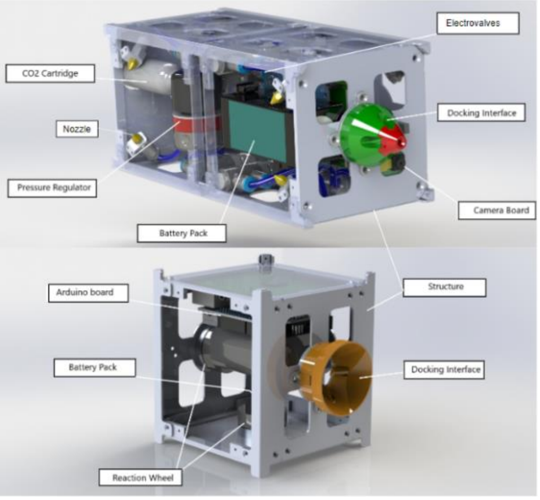

Figure 1. Chaser and Target mock-ups [1]

The Chaser is a 2U CubeSat mock-up (20x10x10cm) and is equipped with a cold gas propulsive system for the position and attitude control and a localization subsystem to recognize the Target. The dedicated proximity navigation software uses the information obtained by the localization subsystem to calculate the path to reach and dock the Target. The Target is a 1U CubeSat mock-up (10x10x10cm) equipped with reaction wheels for attitude control. The mock-ups are equipped with probe-drogue miniaturized docking interfaces [10], composed of an active probe on the Chaser and a passive drogue on the Target. The connection between these two interfaces is obtained with a physical insertion of the two and then a mechanical interlock thanks to a servo motor that rotates the tip of the probe.

The experiment is composed of four main phases (reported in Fig.2):

1. Release phase: the mock-ups are released from their initial electromagnetic constraints into a free-flying condition.
2. Path planning phase: the Chaser localize the Target and compute the trajectory to reach it.
3. Proximity navigation phase: the Chaser approaches the Target by controlling its velocity and attitude, while the Target maintains the initial alignment.
4. Docking phase: the Chaser actuates the servo motor of the docking interface to lock the two mock-ups together.

After each manoeuvre, an experiment operator relocates both mock-ups for the next parabola.

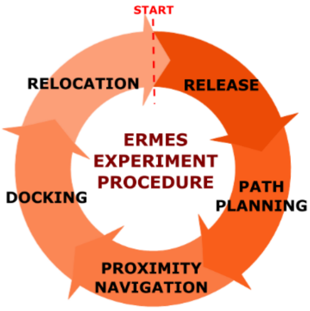

Figure 2. Experiment procedure [2]

5. GNC systems

Due to the complexity of the manoeuvre and the high level of autonomy that the mock-ups have, the main focus in the design and development of ERMES has been dedicated to the GNC systems. The GNC system of each mock-up is composed mainly by the two actuators subsystems and the dedicated software to perform the manoeuvre. Therefore, the following subsections are dedicated to these defining subjects.

5.1. Chaser - Actuators system

As mentioned in the previous section, the Chaser has to follow the trajectory, computed by the proximity navigation software, by actuating its thrusters. In particular, it is equipped with a propulsive system based on expendable CO_2 cartridges and characterized by a set of 8 actively controlled thrusters. The main components of the pneumatic system are: (1) a pressure regulator to set the working pressure at *2.5 bar*; (2) electrovalves, that are the actual actuators controlled by the on board computer system to vary the flow to the nozzles; (3) the nozzles to accelerate the flow. In particular, the nozzles are simply convergent, instead of a classic convergent-divergent configuration due to the necessity of avoiding supersonic flows since the experiment takes place at standard atmospheric pressure and not in a vacuum chamber. In fact, supersonic flows lead to shock waves, that could cause unwanted increase in pressure in the pneumatic system and, consequently, damages to the system or simply alter its performance. The choice of a convergent solution allows also to model the thrust output linearly with the respect to the pressure set on the regulator. In fact, for pressure higher than *1.8 bar*, the flow exits at a sonic state (Mach number equal to 1) and, therefore, the exit pressure is a function of only the total pressure set on the regulator (Eq.1). Consequently, the thrust is linear too (Eq.2).

$$p_{sonic} = p_{total} * \left({}^{2}/_{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \qquad (1)$$

$$T = A_{exit} * p_{total} * \Gamma_{(\gamma)} \qquad (2)$$

The thrusters are divided into two groups of four thrusters each that are positioned in two opposite faces; these groups are further divided into couples of thrusters pointing towards the same point (Fig.3). This tilted configuration allows control over both its attitude and position (6 Degree of Freedom). To move or rotate along a single axis four thrusters must be actuated together as shown in Table 1.

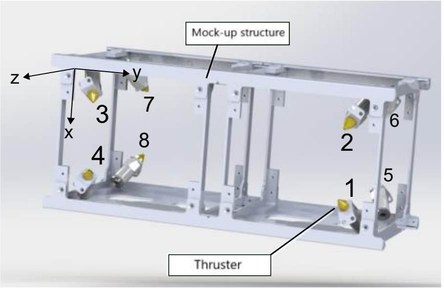

Figure 3. Thrusters configuration [3]

Table 1. Thrusters to be actuated (see Fig. 3) to control the different Degrees of Freedom [1]

	Translation		Rotation	
	+	**-**	**+**	**-**
x	1458	2367	3456	1278
y	1256	3478	1467	2358
z	5678	1234	2468	1357

The electrovalves are controlled with a 30 Hz Pulse Width Modulation (PWM) with 16 steps, that determines the duty cycle of the valve. It is important to highlight that the 16 steps are not related to a standard 4 bit PWM, but a fictitious 8 bit PWM with only 16 possible values instead of 256. The tests of the PWM control were based on a set of laboratory experiments. The pneumatic circuit consisted in a nozzle, an electrovalve, a pressure regulator and a CO_2 cartridge. The pressure regulator guaranteed a constant pressure in the pneumatic system. Thrust data were acquired with a load cell connected to the support plate of the nozzle. Initially, the data acquisition dealt with the 256 steps (8 bit) PWM so that the real trend could be plotted. As expected, the real trend is a sigmoid with the initial values around zero because for low value of duty cycle the electrovalve does not have the time needed to react to the signal and consequently completely open (Fig.4, first graph). Therefore, the number of steps available has been restricted in a way that makes it linear with the respect to the duty cycle values. This choice greatly simplifies the control of the actuators. The simplification lies in the shift from a real sigmoid trend to an ideal linear trend of the thrust. The next step was to find 16 out of 256 values of duty cycle that could approximate a linear trend of the thrust. Finally, this new fictitious 16 steps PWM has been tested by sending random step-like commands of duty cycle to the electrovalves. The resulting trend (Fig.4, second graph) well approximates the desired linearity.

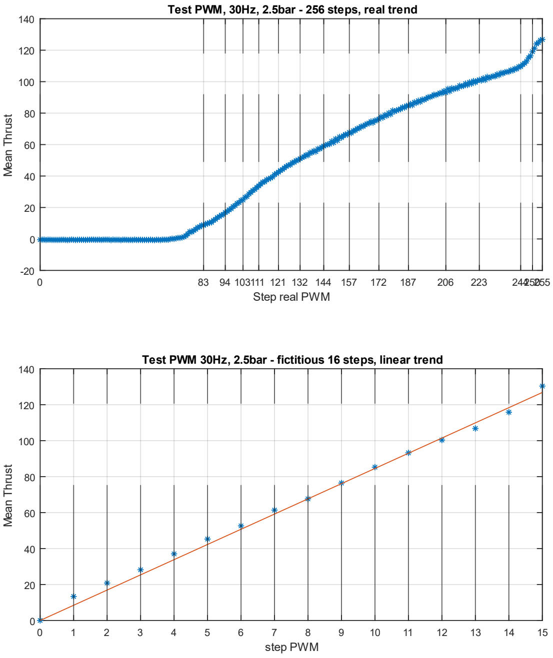

Figure 4. PWM linearization [4]

5.2. Target - Actuators system

Differently to the Chaser, the Target has a simpler actuators system due to the fact that it has to control a lower number of Degree of Freedom (three rotations). It is composed of a set of three reaction wheels along three perpendicular axes (as shown in Fig.5). The reaction wheels are composed of a brushless DC motor and a flywheel to increase the moment of inertia.

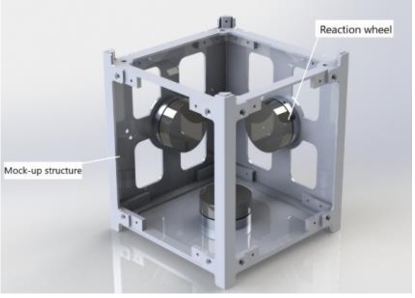

Figure 5. Reaction wheels configuration [5]

Reaction wheels are widely used for attitude control because of their manufacturing and control simplicity. They react by contrasting unwanted disturbances to maintain the angular momentum constant and fixed, but they can be used also to perform attitude manoeuvre. In ERMES both these features can be implemented, in fact the Target can maintain its orientation with the respect to the initial alignment or by pointing towards a specific point during all the manoeuvres. These two different behaviours can be compared to find the best approach in order to successfully dock.

5.3. Proximity Navigation software

The Proximity navigation software is based on three main levels (as shown in Fig.6). It runs thanks to an on-board computer system mounted on the Chaser, that is composed of an Arduino and a Raspberry board as main units and employs a set of sensors for data acquisition. The main sensors are Inertial Measurement Units (IMU), proximity sensors and a camera for the localization system. The on-board computer system includes also a current monitoring module and a sensor to trigger the locking mechanism of the docking interface. Between the two mock-ups, only the Chaser needs to recognize the other and compute the path needed to dock, therefore the Target is equipped with a simpler on-board computer system, that comprehends IMUs and an Arduino board.

The Low Level deals with the control of the actuators and it runs on the Arduino boards. In the Chaser, it receives step-like commands of variation of acceleration along a certain axis from the medium level and actuates properly the thrusters. In particular, it is composed of 6 independent closed-loops Single Input Single Output (SISO) dedicated to a single Degree of Freedom each. The feedback is guaranteed by the IMUs, from which the low-level extracts information about the linear and angular accelerations. As mentioned, the input is a step-like command of acceleration, while the output is the duty cycle of the valve needed to actuate the command. In the Target, the control system is based on a closed-loop control system of the reaction wheels. The output of the control is the velocity of the three actuators to contrast the torques read by the IMUs, which represent once again the feedback of the system.

The Medium Level deals with the recognition of the Target, path calculation and command submission (via UART communication). It runs on the Raspberry board, which has been delivered with an Ubuntu 20.04 Server installation and the Robot Operating System (ROS) Noetic framework [11] [12]. The localization system is based on an AprilTag Detection [13] [14] [15] for the visual perception, then the data acquired from the camera are used to have information regarding the distance and twist of the Chaser with the respect to the Target (that represent the only valid reference point). In particular, the twist is calculated by deriving the pose provided by the computer vision algorithms. The whole software implements two Extended Kalman Filter (EKF), one to fuse sensors that have continuous read (like the IMU) and one to fuse all sensors (IMU and computer vision-based localization). This system, although it is standard, gives us a particular advantage: it allows to differentiate the relative movement between Target and Chaser, discerning if it is caused by a movement of the Target or a movement of the Chaser. Moreover, the estimation is continuous and, for small intervals of time, has a negligible error. The Raspberry can execute 2 types of trajectories: one that adjusts one axis at a time, and another that tries to optimize the quadratic problem of finding a trajectory that requires the minimum amount of fuel. After calculating the trajectory, it sends the relative commands to send o the lower level.

Finally, the High Level is the control level for the experiment operators, in fact it runs on a laptop. It does not interfere with path computation or data handling; it is needed just to start the manoeuvre by sending the command to initiate the releasing phase.

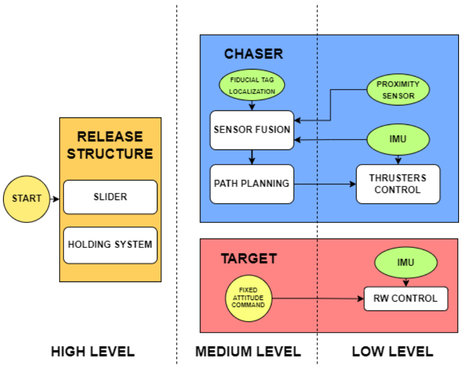

Figure 6. Software architecture [6]

6. Conclusions

ERMES focuses on autonomous docking manoeuvres with miniaturized systems; it investigates not only design solutions and components but also possible software architectures for high reliable autonomous systems. Moreover, it delas with discussing the efficiency and robustness of the software approach in relation to the actual manoeuvres during the parabolic flights. In this paper the design of the main subsystems of the experiment is presented. However, the interest is the integration of all the systems and the simulations of the manoeuvre, initially in the laboratory and then during the campaign. The simulations in the laboratory will be performed on a low-friction table and will concern the validation of two-dimensional docking manoeuvres so that the critical points can be evaluated and eventually corrected in view of the final test in a reduced-gravity environment during the flight campaign.

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