UNIVERSITÀ
DEGLI STUDI
DI PADOVA

DIPARTIMENTO
DI INGEGNERIA
DELL'INFORMAZIONE

MASTER THESIS IN ELECTRONIC ENGINEERING

Electric and Electronic Design of a CubeSat mock-up tested in microgravity environment

MASTER CANDIDATE

Mattia Dignani

Student ID 2028781

SUPERVISOR

Prof. Francesco Branz

Università degli Studi di Padova

ACADEMIC YEAR
2022/2023

"Prova a lasciare un segno"
Fabri Fibra

Abstract

This master thesis has the object to show and explain the electrical and electronic part of EMRES, Experimental Rendezvous in Microgravity Environment Study, that is a project carried on by a group of master students which studied and tested an autonomous docking manoeuvre between two free-flying CubeSats mock-ups in a reduced gravity environment.
The experiment took part in the 79^{th} ESA Parabolic Flight Campaign, following the selection for the "Fly Your Thesis! Programme" 2022.
The thesis will show the electrical and electronic system design of the two mock-ups, called Chaser and Target, and of their release systems, composed by a rack and a slider. The two mock-ups involved in the experiment are equipped both with a Guidance Navigation and Control (GNC) system and miniaturized docking interfaces. During the manoeuvre the Chaser is active while the Target is cooperative.
Moreover, at the end, it will explain the result of the experiment, general thoughts regarding the object of this thesis and some general improvements to help the students who will continue or they what to improve ERMES.

Sommario

Nel panorama della moderna esplorazione spaziale, CubeSats si sono affermati come veicoli innovativi e accessibili per esperimenti scientifici, osservazioni terrestri e progetti di educazione scientifica. La miniaturizzazione dei satelliti, con l'introduzione di moduli CubeSat standardizzati, ha aperto nuove prospettive per la ricerca spaziale, rendendo l'accesso allo spazio più economico e accessibile a un vasto pubblico.

Experimental Rendezvous in Microgravity Environment Study (ERMES) è un progetto studentesco che ha come obiettivo primario progettare e testare una manovra di docking autonomo tra due prototipi di CubeSats rilasciati in un ambiente a gravità ridotta. I due prototipi coinvolti nell'esperimento sono dotati di sistemi di Guida, Navigazione e Controllo (GNC) e di interfacce di docking miniaturizzate. La manovra avviene in una configurazione Target-Chaser, nella quale il Chaser è attivo mentre il Target è cooperativo. Le condizioni di gravità ridotta sono state ottenute partecipando alla 79^a Campagna di Voli Parabolici dell'Agenzia Spaziale Europea (ESA), a seguito della selezione per il "*Fly Your Thesis! Programme*" 2022.

Questa tesi presenta i sistemi elettrici ed elettronici progettati e realizzati per i due Cubesat e il loro sistema di rilascio. Verrà esposto generalmente cosa sono, la loro funzionalità e verranno mostrati i vari componenti utilizzati e come sono stati progettati per ogni sistema elettronico. Successivamente verrà trattata la descrizione del design dell'esperimento e della procedura sperimentale; infine verrà discusso l'esito della campagna di test attraverso l'analisi dei risultati.

Contents

List of Figures

List of Tables

Nomenclature

Indices and Acronym

AWG	American Wire Guage
DoF	Degree of Freedom
E/E	Electric and Electronic
ERMES	Experimental Rendezvous in Microgravity Environment Study
ESA	European Space Agency
FYT	Fly Your Thesis
GNC	Guidance Navigation and Control
IMU	Inertial Sensor Unit
MOSFET	Metal-Oxide-Semiconductor Field Effect Transistor
NiMh	NIckel-Metal Hydride
OBCS	On Board Computer System
PCB	Printed Circuit Board
PIO	Pin Input and Output ports
PLA	Polylactic Acid
RW	Reaction Wheel
SIO	Super Input and Output (Serial Communication)
ToF	Time of Flight

Symbols

A	Ampere
Ah	Ampere hour
I_D	Drain current
V	Volt
$V_{DS,br}$	Breakdown Drain to Source Voltage
V_{DS}	Drain to Source Voltage

Chapter 1

Introduction

In the landscape of modern space exploration, CubeSats have established themselves as innovative and accessible vehicles for scientific experiments, terrestrial observations and science education projects. The miniaturization of satellites, with the introduction of standardized CubeSat modules, has opened up new perspectives for space research, making access to space cheaper and accessible to a wide audience. A CubeSat Mockup represents a physical replica of the satellite, allowing engineers and scientists to closely examine the structure, component layout, and other critical aspects without having to deal with the costs and risks associated with building a working satellite. Among the many challenges that the space environment poses, the study of movement in microgravity emerges as a crucial area, with significant impacts both on the design of space missions and on the understanding of fundamental physical principles.

Particularly, *Experimental Rendezvous in Microgravity Environment Study*, or simply ERMES, is a project of the University of Padua carried out by Master Degree students from different academic backgrounds. ERMES has the aim to develop and test two Cubesat mock-up an autonomous docking experiment made by two free-floating CubeSat mock-ups in a reduced gravity environment.

A space rendezvous is a series of consecutive orbital manoeuvres which allow two spacecraft to reach the same orbit and get closer up until a very short distance. The docking manoeuvre is completed when a connection between the two is established. In particular, space rendezvous are divided into three major phases:

- the first phase of fly-around, which is needed to insert one spacecraft in an orbit around the other;

Figure 1.1: ERMES Official Logo

- then an approaching phase, which aims at closing the distances;
- lastly, a phase of proximity navigation that includes all the adjustments before the actual docking.

ERMES has the focus on the third part. The proximity navigation maneuvers in space are delicate operations performed by spacecraft to move safely and controlled in the vicinity of other celestial bodies, such as satellites, space stations or asteroids. These maneuvers require sophisticated control algorithms, as well as precise knowledge of the spacecraft's position and orientation. However, space missions involving small satellites don't afford human monitoring, therefore they must rely on sensors and software solutions to accomplish this particular task. Thereby, more efficient and reliable proximity navigation and control systems for autonomous small satellites are of great interest, due to their effectiveness in several applications.

The two mock-ups involved are named "Target" and "Chaser" and they are the main components of the experiment, while the Release System sustained and attended them during the experiment. The Chaser actively performs the manoeuvre by approaching the Target and docking, while the Target acts cooperatively by contrasting unwanted attitude disturbances. Both mock-ups are equipped with Guidance Navigation and Control (GNC) systems suitable for their role. In particular, the Chaser is equipped with a cold gas (CO_2) propulsive system characterized by a set of 8 simple convergent nozzles, which allows the Chaser

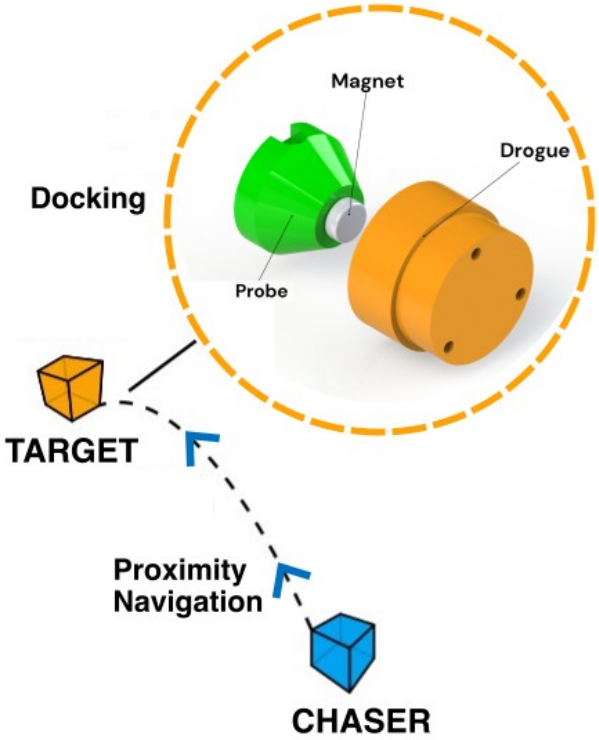


Figure 1.2: Schematic description of ERMES manoeuvre

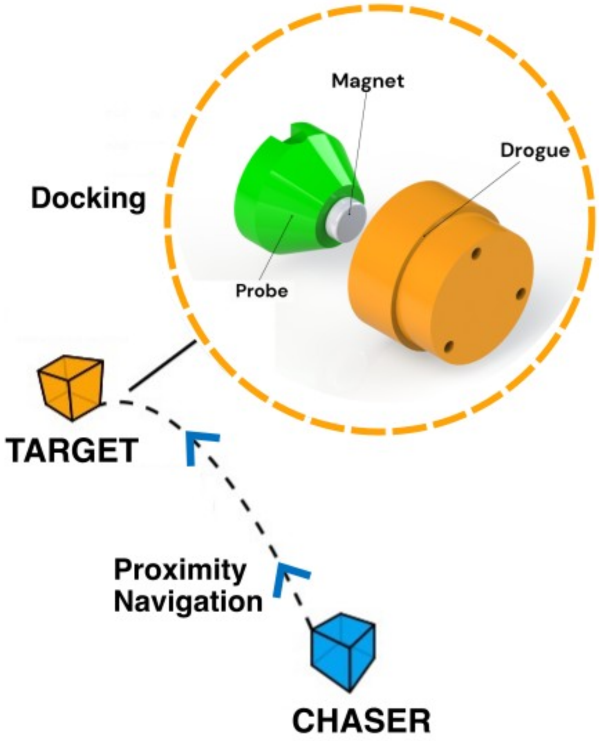


Figure 1.3: Chaser and Target

to control all its 6 Degrees of Freedom (DoF); while the Target is equipped with three Reaction Wheels (RW), which allow controlling only its attitude (3 DoF). The manoeuvre is accomplished by releasing the CubeSat mock-ups from their initial electromagnetic constraints into a free-floating condition, then the dedicated localization and proximity navigation software permits the Chaser to find and reach the Target.
The reduced-gravity environment is achieved by boarding the experiment on a parabolic flight. This particular experimental platform guarantees a low level of gravity aboard, that can reach values lower than $0.01g$. It is important to underline that this experiment was carried out in a specific environment condition which is not possible to reproduce easily. Moreover, the Chaser and Target worked in the space, so it is important to underline that there are three axis of reference, called x-y-z for simplicity in Fig.1.4, to take count for both mock-ups. In the aeronautical, nautical or automotive field, each rotation around one axis have a name:

- if the rotation is around the x axis, the rotation is called roll;
- if the rotation is around the y axis, the rotation is called pitch;
- if the rotation is around the x axis, the rotation is called yaw;

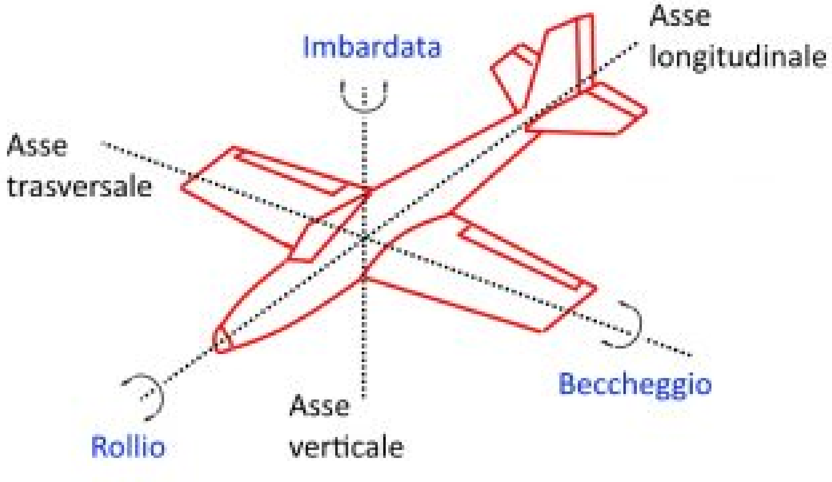


Figure 1.4: Reference axis: x-y-z

1.1 Electric and Electronic System

The Electric and Electronic System (E/E) system is one of the most important part in the designed of the experiment. Chaser, Target and their Release System have different E/E system. Generally an E/E system has a lot of requirements to be respected, such as the design of the battery pack and if it can supply the load of the system, the safety of all the components, such as placing a correct fuse before a supply of the component, or using the correct AWG wire to avoid the possibility of fire. The Chaser has a complex E/E system composed by a battery, three electronic boards such as a RaspberryPi 4 for the high level language, an ArduinoNANO to control the propulsive system and an ArduinoUNO to get the data during the experiment from sensors, as in Fig.2.15. Moreover, the ArduinNANO controls the opening/closing of the electrovalves through the use of a PCB, composed by eight MOSFETs.

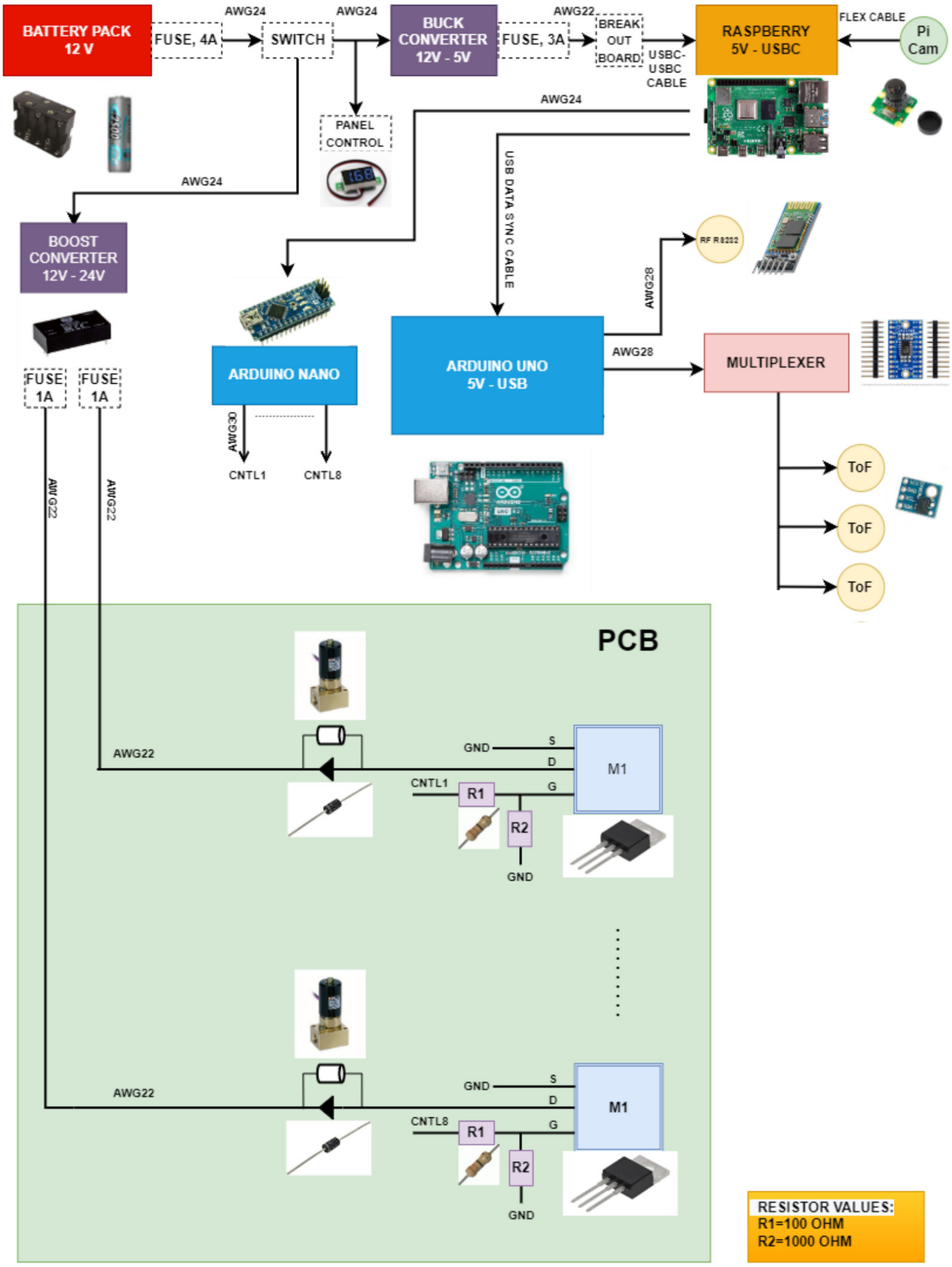


Figure 1.5: E/E system schematic of the Chaser

The Target has a simple E/E system, composed by the battery, two electronic boards, a Motor Shield V2 plugged-in into a ArduinoMEGA used to control the Reaction Wheels and the IMU (Inertial Measurement Unit) sensor. One Reaction Wheel is composed by one flywheel attached to a DC motor, which is controlled by the driver. The Arduino MEGA get the data about the initial position of the Target and the driver controls the Dc motor speed to delete the angular momentum of the Target. In this way, the Target remains still during the microgravity phase of the experiment.

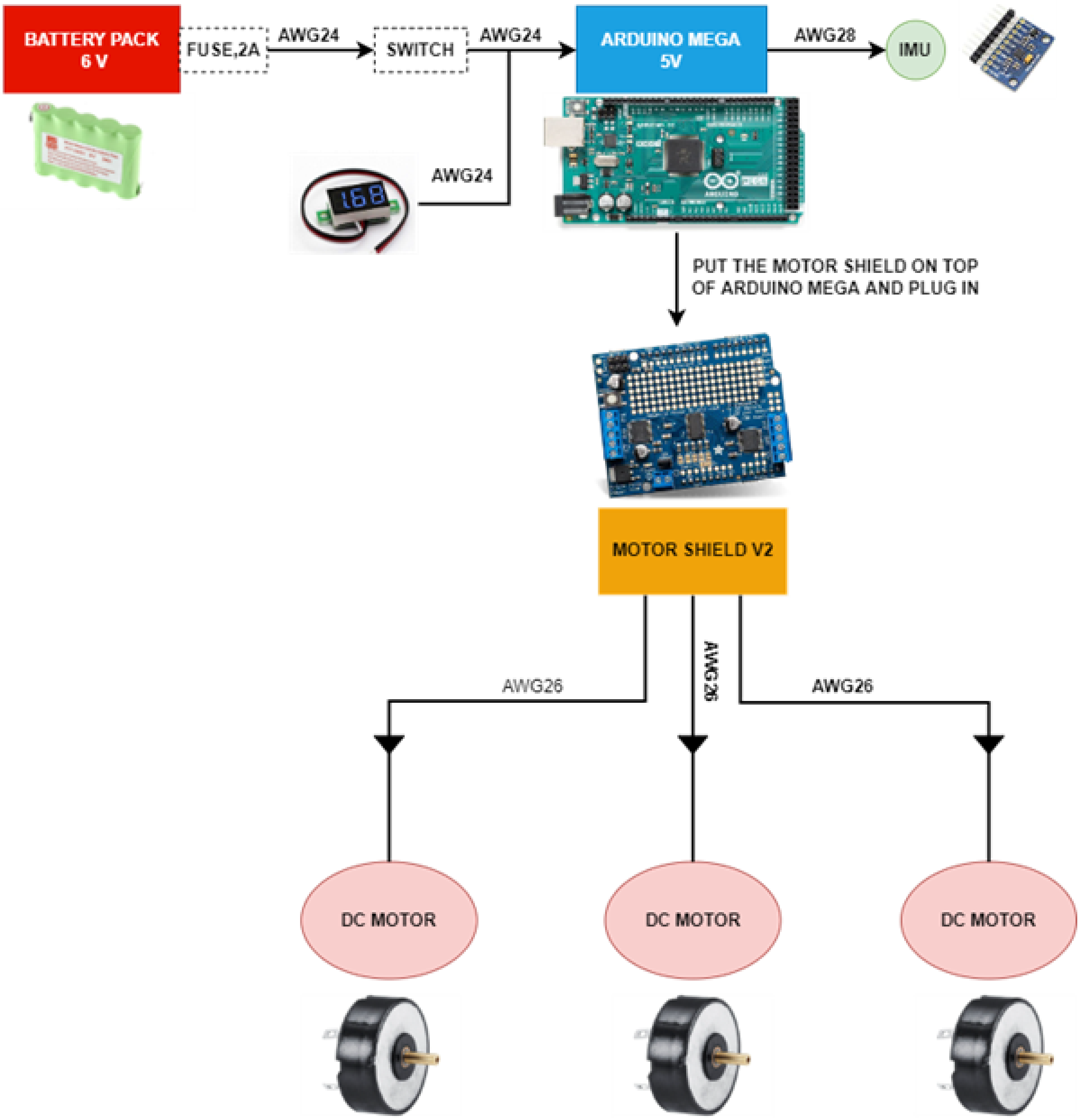


Figure 1.6: E/E system schematic of the Target

The Release System has a simple system composed by an ArduinoMEGA to control the sliders and an switching converter to supply the electronic board and the slider. It has also another switching converter which supplies the electromagnets used to attach both mock-ups to the Release System. The Release System has the only task to release Target and Chaser in different ways during the experiment, when the microgravity starts, as in Fig.2.41).

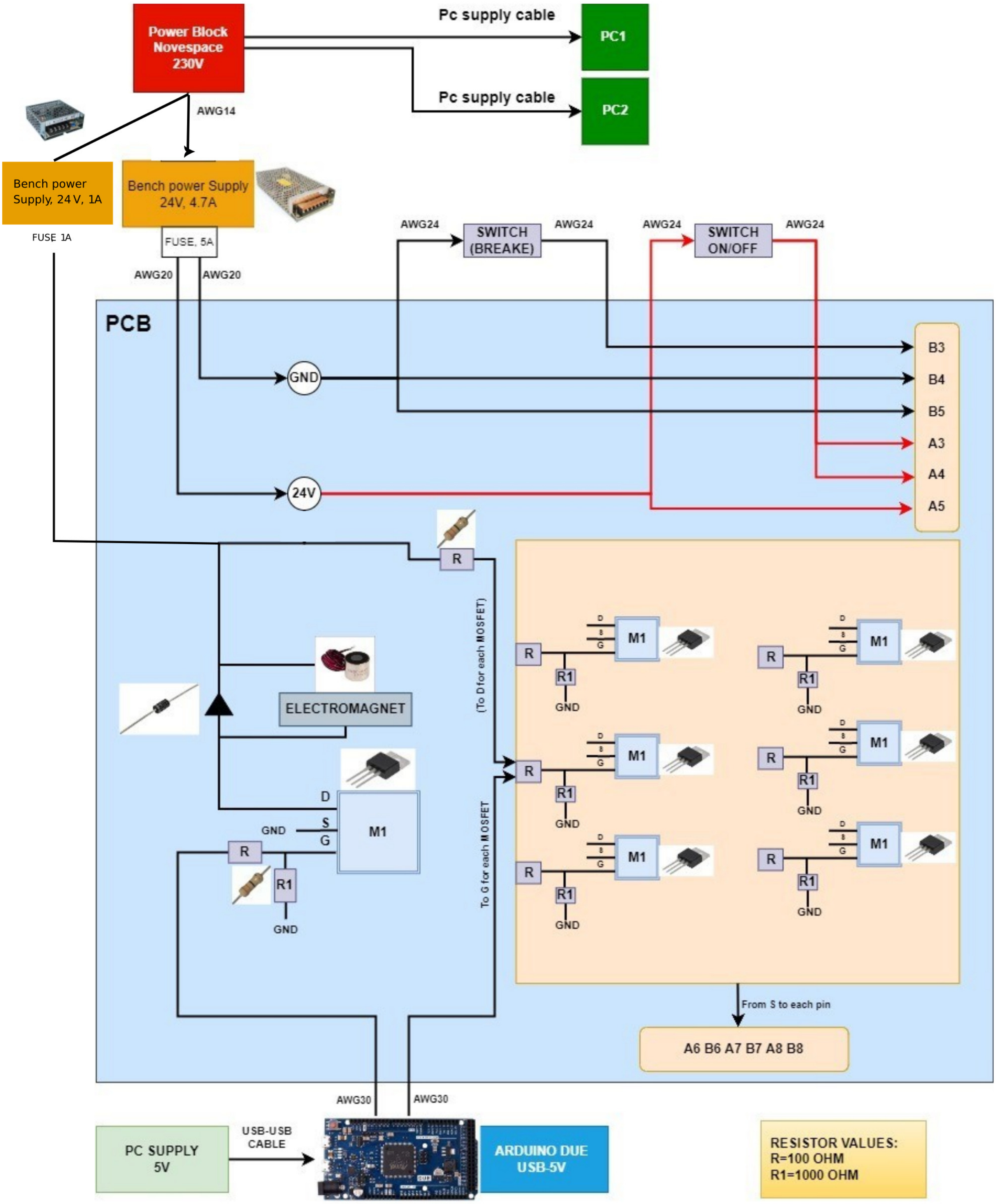


Figure 1.7: E/E system schematic of the Release System

1.2 Safety of the project

The safety was one of the main argument in this project. Functional safety is that part of the overall safety (of a system, equipment or plant) that depends on the absence of unacceptable risks caused by malfunctions or failures. As such, functional safety is a feature of the system; in the design of systems, plants and other technological equipment, there are several processes and methodologies useful to ensure that a product has an adequate level of functional safety. The functional safety is one of the most important aspects in a project because it has the aim to avoid any type of risk and physical or environmental damage. During the design and the developing of the project, great importance has been given to the functional safety of the E/E system. For the purpose, a document called "GDL-Guidelines" [15] was studied by the team, provided by two companies, Novespace and the European Space Agency (ESA), which followed step-by-step the entire project. This document gives details and explanations for the requirements and offers technical solutions for meeting them, such as the safety analysis, the materials and quantities permitted, or the electrical design and its safety. During the develop of the project, ESA and Novespace underlined often that the safety is the most important thing in a project. The safety of the airplane where the experiment took part was really important for Novespace because during the parabolic flight it is really difficult to avoid any type of damage so it's fundamental that all the system have a safety program or components to prevent any damage. Moreover, it was important also to ensure the structural security of the experiment. The two mock-ups and the Release System have metal part but also sharp corners which are dangerous both for the pepole inside the airplane and for the both Cubesats. So they were covered by a rubber material to decrease the possibility to hurt the people in the airplane. A net was set up around the experiment to avoid the free flight of the Chaser and Target around the airplane during the low gravity environment.

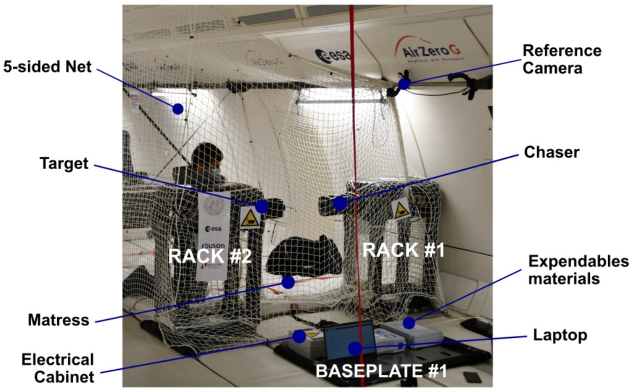


Figure 1.8: Cabin layout of the experiment

1.3 ESA Fly Your Thesis! Programme 2022

The ESA "Fly Your Thesis! Programme" [11] is educational programme held by the ESA Education Office for students to propose, design, build, test and fly their experiment on board a parabolic flight. The Parabolic Flight Campaign takes place in Bordeaux (France), at the facilities of Novespace [14], which is the company that owns and operates the Airbus A310. The Campaign features 3 flights with 31 parabolas per flight.
This Programme aims at giving students the experience of working in a professional project environment, while simultaneously allowing them to gain valuable experience and improve their skills and professional network.

Figure 1.9: ESA "Fly Your Thesis! Programme" Logo

1.3.1 Parabolic Flight

Parabolic flights are a particular type of testing platform, which provides a brief near-weightless environment for scientific and technological investigations. A parabolic flight consists on an airplane that makes parabolas during the flight. This particular trajectory that guarantees $22s$ of low-gravity phase (generally lower than 0.01g) at the top of the parabola, while during the ascendant and descendant phase the gravity is almost double (2g). The trajectory is divided into four main phases, shown in Fig.3.4:

1. **Standard-gravity phase**: initially the plane is flying straight, therefore the gravity level perceived is 1g. During this phase all the preparations for the experiment take place. The duration of this phase can vary depending on a series of factors.

2. **First Hyper-gravity phase**: the plane starts the ascendant phase, reaching an angle of 45°. The perceived g-level is around 1.8. In this phase, the experimenters are anchored to the floor thanks to seatbelts. This phase lasts around $20s$.

3. **Low-gravity phase**: when the plane reaches the top of the parabola, the pilot lowers the engine power and the plane starts free-falling. Inside the plane, the perceived g-level drops under 0.01g for around $22s$. During this phase, the experiment takes place.

4. **Second Hyper-gravity phase**: finally, the plane starts the descendant phase, reaching an angle of 45° and return to the standard-gravity phase, where the gravity is again 1g. This phase is analogous to the previous hyper-gravity one.

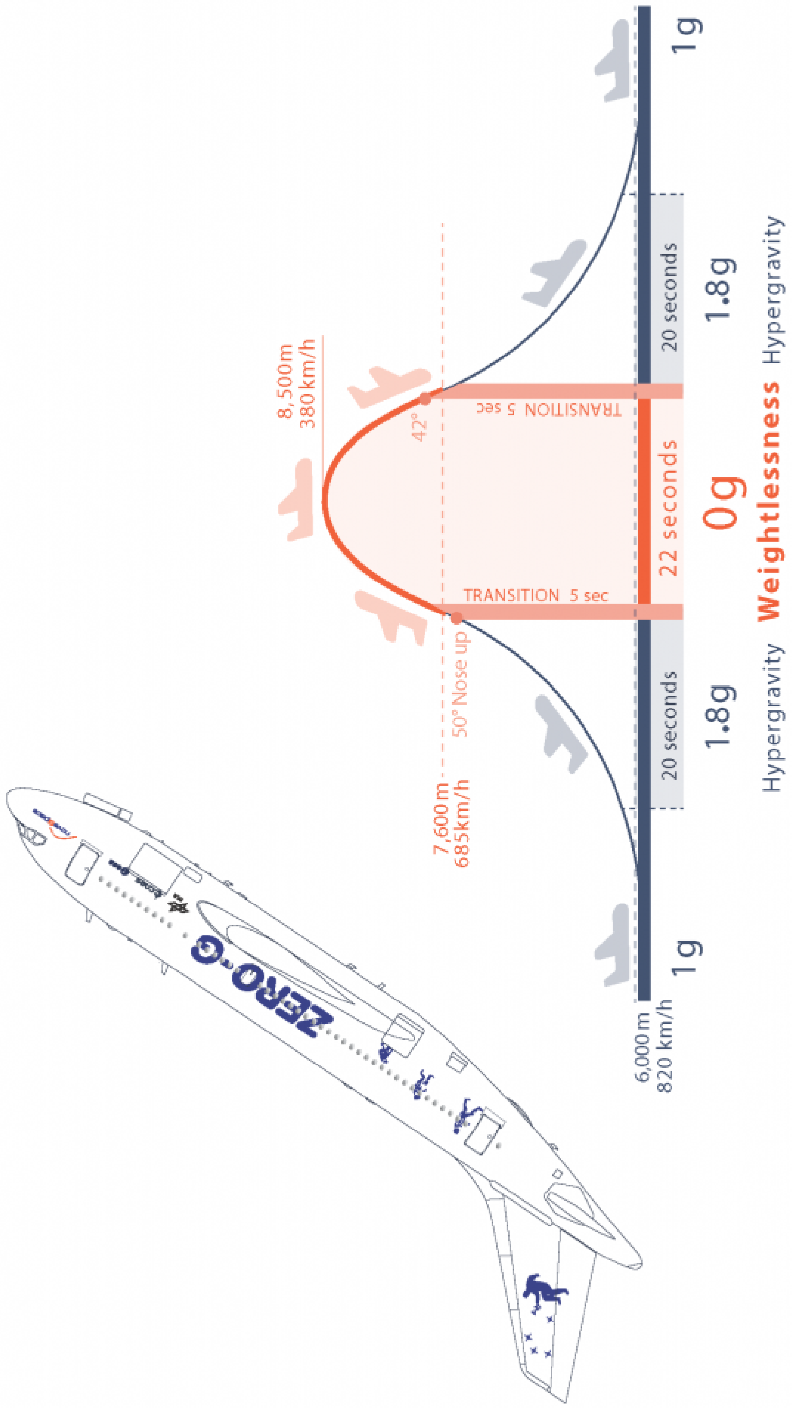


Figure 1.10: Parabolic Flight Scheme

Chapter 2

Experimental Setup

In this chapter the experimental setup will be shown, characterized by the Chaser, the Target and the Release System. It will provided a list of all the components of Chaser, Target and the Release System and the design process for the power supply used, the PCB used in Chaser and Release System, the wiring and the power budget.

The power budget is an analysis process performed on the power delivery network from input to electrical or electronic loads by identifying the power consumed by each electrical functional block and the power dissipated during the power delivery. It will be described and explain, with a table which resumes the input and output values of the voltage, current and power of the electronic components. It is important to remember that all the values of voltage and current are extracted from the datasheet of the component, while the power is calculated through the formula $P = V \times I$. The power budget and the power supply design are strictly connected because it is important to know the power requirements of all the components before the right choice of the power supply. Another important step of the E/E system design is the wiring. It was used the American Wire Gauge (AWG) which is a standardized system for measuring wire cross-section[1], shown in the table 2.1 below, provided by Novespace, through the Guidelines[15].

There will be a description of the cabin layout of the experiment on the airplane. At the end there will be a on-ground test of the experiment in the laboratory with a low-friction table.

Wire cross-section		**Max Current Capacity (A)**
AWG	mm^2	
30	0.05	1.3
28	0.08	1.8
26	0.12	2.5
24	0.2	3.3
22	0.32	4.5
20	0.32	6.5
18	0.82	9.2
16	1.25	13
14	1.5	19
12	2.5	25
10	4	33
8	6	44
6	10	60
4	16	81
2	25	108
0	50	147

Table 2.1: Wiring table

2.1 Chaser

The Chaser is a high-performance CubeSat mock-up which has the 'active' role to trace the trajectory and to make the docking with the other mock-up, the Target, which has the 'cooperative' role to stay still during the microgravity environment. It is a 2-unit CubeSat which has the dimensions of $200x100x100mm$ [21] and it has an E/E system composed by boards, a printed circuit board (PCB), solenoid valves and sensors collaborating between each other, shown in Fig.2.15.

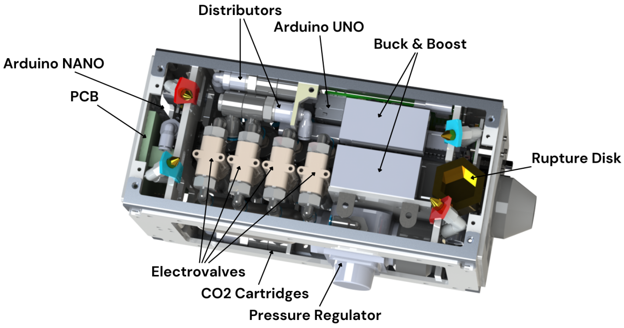


Figure 2.1: Chaser - internal structure design

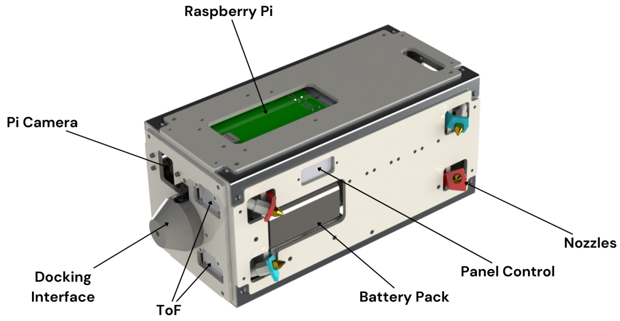


Figure 2.2: Chaser - external structure design

2.1.1 Electronic components

In this subsection, a list of the components of the Chaser will be provided.

1. The battery pack in Fig.2.36 is composed by 10 *Ansmann NiMH* rechargeable cells. Each cell provides a voltage of 1.2 V, a capacity of 2.5 Ah and a maximum discharge current of 5000 mA. The cells are connected in series, so the total voltage is 12 V. The battery pack has a double connection with the buck converter and the boost converter. Between the battery pack and the two converters there are a switch to turn on and off the battery, a display to check the battery voltage, and a fuse as protection for the system.

Figure 2.3: Battery pack of the Chaser

2. The boost converter *Mean Well MDS20A-24*[9] increases the voltage from 12 V at the input to the 24 V at the output to supply the solenoid valves. At the output there are two fuses, to protect four solenoid valves each.

3. The buck converter *Mean Well MDS20A-5*[9] decreases the voltage from 12 V to the 5 V needed for the powering of the Raspberry Pi4. At the output there is a fuse to protect the Raspberry Pi4.

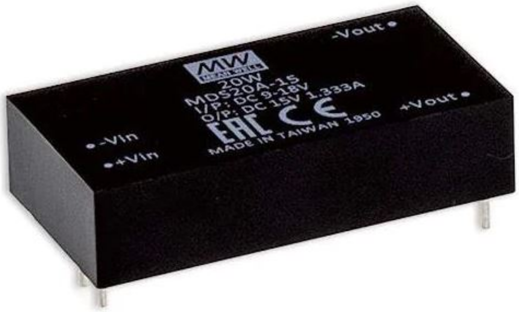


Figure 2.4: MDS Boost and Buck converter

4. A break-out board, the *SparkFun BOB-15100 USB-C Breakout Board*[6], is implemented so that it works as an adapter between the buck converter and the Raspberry Pi4.

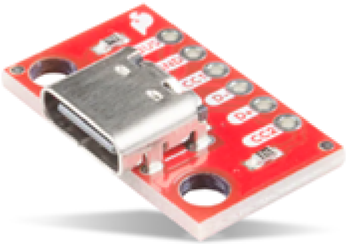


Figure 2.5: Breakout board

5. The main board is the Raspberry Pi4. It is connected to the breakout board via USB type C cable. The Raspberry is directly connected to the PiCam, to the Arduino UNO through USB cable type B and to the Arduino NANO via USB mini cable type B. The Raspberry PI4 has the main role to elaborate the data of the sensors sent by Arduino UNO, to compute the trajectory and sent the relative commands to the Arduino NANO to properly actuate the solenoid valves.

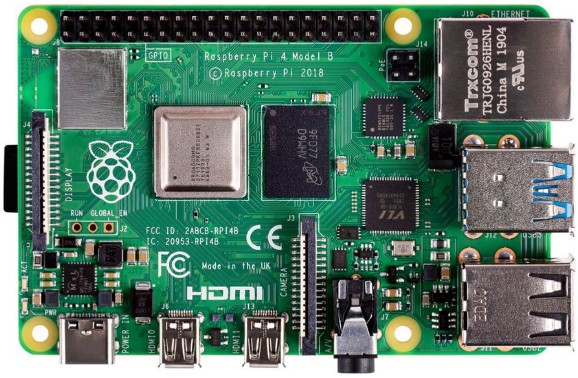


Figure 2.6: Raspberry Pi4

6. The first connection with Raspberry Pi4 is Arduino UNO. Arduino UNO is linked to the multiplexer and allows the connection *I2C* with three ToF, taking information from sensor and sending these to the Raspberry Pi4 that computes high level calculus.

Figure 2.7: Arduino UNO

7. The second connection with Raspberry Pi4 is the Arduino NANO. It is used to control eight MOSFET connected in series to the solenoid valves. The connections to the 8 Gate ports of the MOSFETs starts from one I/O pin of Arduino NANO.

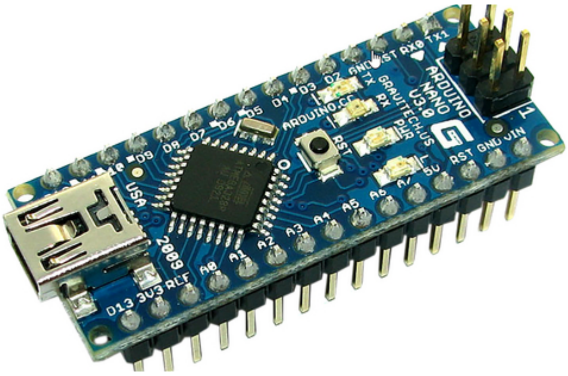


Figure 2.8: Arduino NANO

8. The solenoid valves chosen for the experiment are the *Solenoid Valve PVQ31*[7]. Each solenoid valve is powered by the boost converter and it is controlled electrically by one of the eight MOSFETs: when Arduino NANO set its output pin as high, MOSFET allows the current flow, activating the solenoid valve. Each solenoid valve is connected to the Drain of each MOSFET and to the boost converter through a PCB.

Figure 2.9: Solenoid valve PVQ31

9. A PCB was implemented to ease the connection of the solenoid valve with MOSFETS, the *IRL40B215* [13], and the boost converter, acting as the source of power for the solenoid valve. In this PCB there are eight MOSFETs that has for each a protection circuit composed of two resistors and a diode connected in anti-parallel with the solenoid valve.

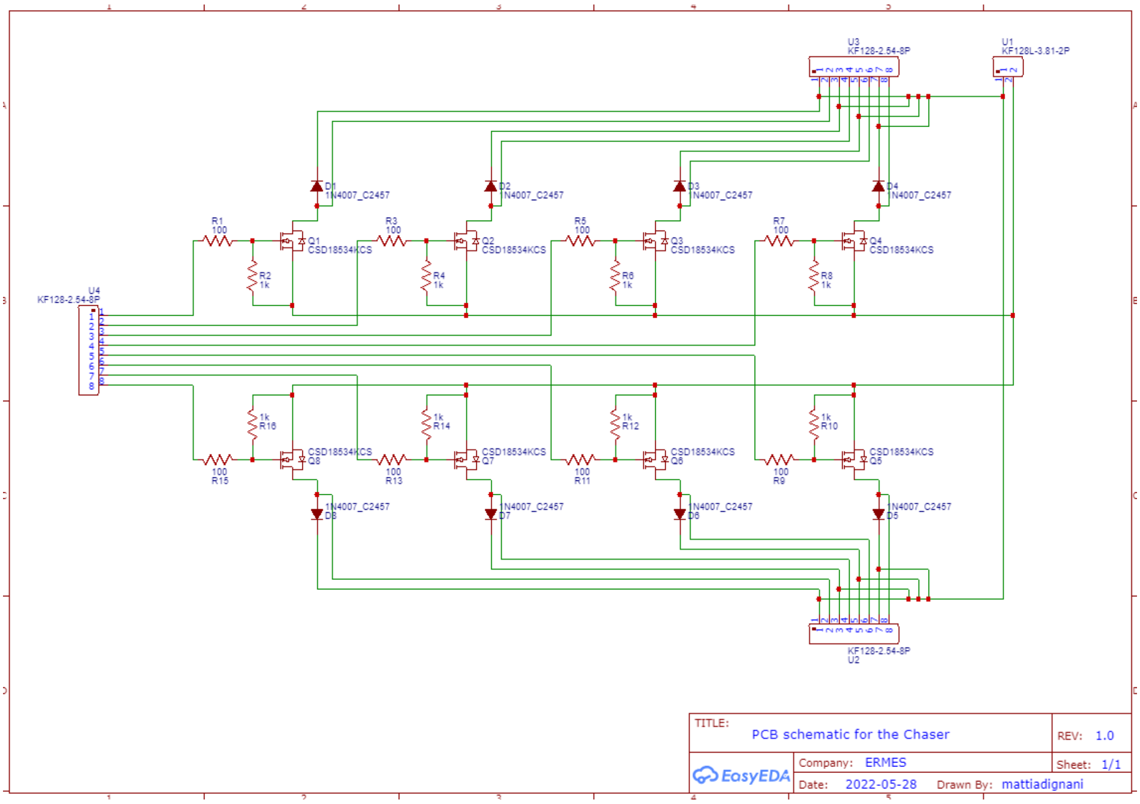


Figure 2.10: E/E schematic of the Chaser

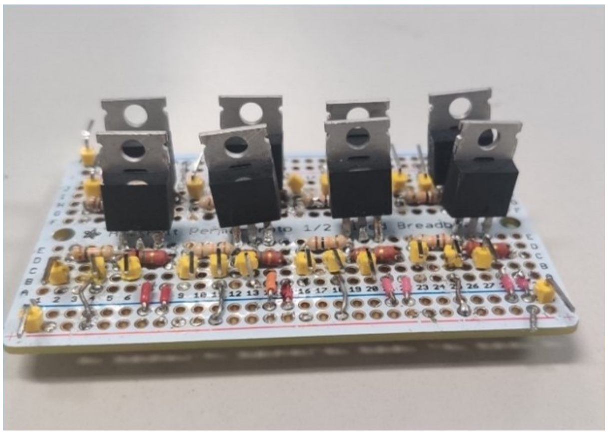
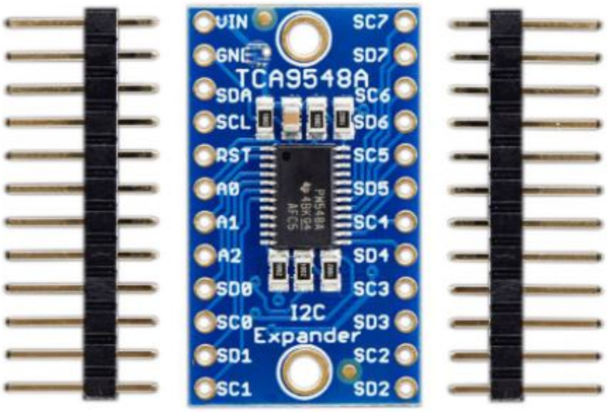


Figure 2.11: Printed circuit board

10. The Multiplexer chosen is the *Adafruit TCA9548A*[4] and it is used to manage and the communication I2C between the Arduino UNO and three ToFs.



L'immagine è solo a scopo illustrativo. Fare riferimento alla descrizione del prodotto.

Figure 2.12: Multiplexer

11. The Sensors that are managed by the multiplexer are three ToF *ST VL6180X*[22]. It uses time-of-flight measurements of infrared pulses to determine the range to a target object, allowing it to give accurate results. In this case, three ToFs are used to have a better precision of the distance between the Chaser and Target.

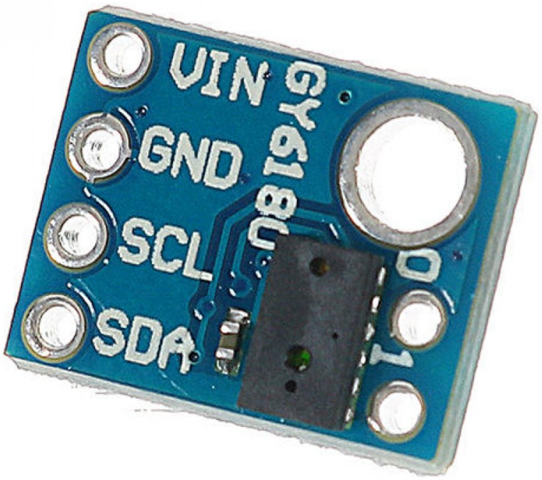


Figure 2.13: Time of Flight

12. The other sensor is the Pi Camera, connected with a flex cable to the Raspberry Pi4. It is used during the first phase of the experiment to check the distance between the Target and the Chaser and it is the main sensor for the localization system via AprilTags.

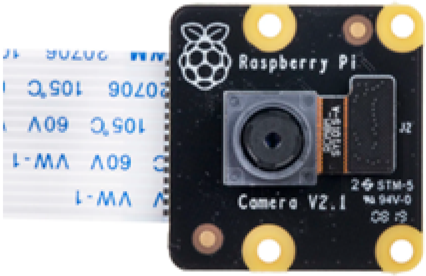


Figure 2.14: PiCam

2.1.2 E/E system

In the Fig.2.15, there is the E/E system of the Chaser.

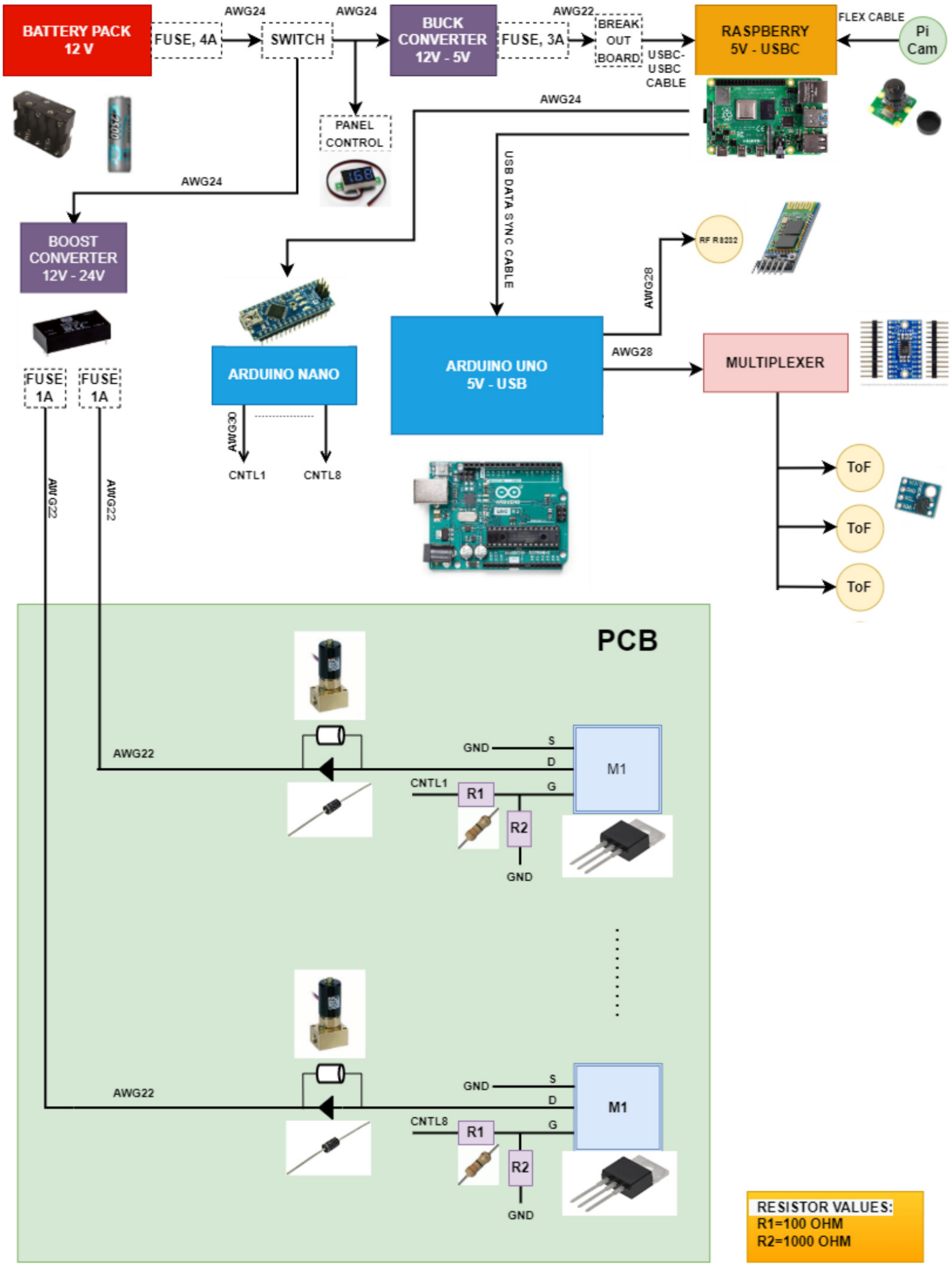


Figure 2.15: E/E system schematic of the Chaser

The on board computer system of the Chaser is the 'core' of the mock-up: it is composed by the three boards, the Raspberry Pi4, the Arduino UNO, the Arduino NANO and the sensors, three Time of Flight (ToF) and the Pi Camera. The

Raspberry elaborates the data from the ToFs, which provide a continuous read of distance between Target and Chaser, and from the Pi Camera which identifies the Apriltags (Fig.2.16) attached to the Target. So, the Raspberry Pi4 calculates the trajectory to follow to allow the docking when the Chaser reaches the Target.

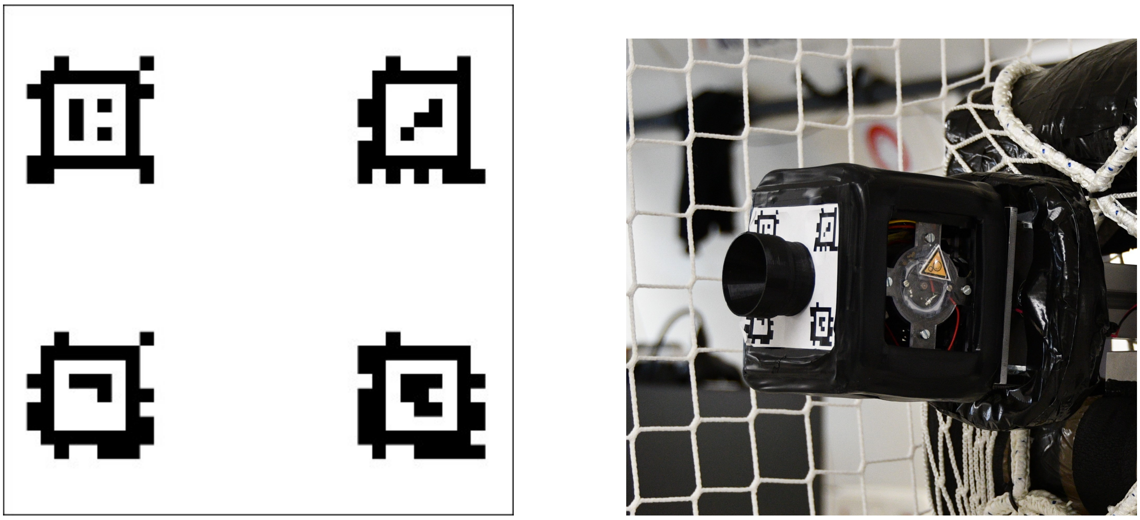


Figure 2.16: Apriltag

After the Raspberry Pi4 get all the data, it calculates the trajectory and send the commands to control the solenoid valve. The Arduino UNO reads the data from the three ToFs and communicates the sensors state to the Raspberry Pi4, while the Arduino NANO controls the opening and closure of the solenoid valve through eight MOSFET according to the commands received by Raspberry through serial communication (UART).

2.1.3 PCB design

One important component of the E/E system of the Chaser is the PCB for the control of the solenoid valves. The PCB design started with the idea to open and to close the solenoid valves to control the propulsive system for the release of the CO_2 from the nozzles. It was used a drilled plate made by copper and the positioning of all the stages was studied to fit perfectly in the dimensions of the plate. The PCB had restrictive requirements in terms of dimensions, because it must fit in the internal structure of the Chaser together with all the E/E system. Consequentially it was decided to choose a plate with dimensions $8cm \times 5cm$. In Fig.2.20 it is shown the configuration of the eight stages of the PCB, and it is composed by:

1. one MOSFET used as logical port in order to permit or avoid the current flow on the solenoid valve. A MOSFET *IRL40B215* was selected for this stage: it is

optimized for Logic Level Drive and it has a fast turn-on and turn-off phase, as seen from the datasheet [13]. Moreover, the solenoid valves are connected in series to the Drain of the MOSFET, and it needs 24 V and 165 mA to be correctly supplied, values that the Drain to Source voltage V_{DS} and the Drain Current I_D of the MOSFET can hold. The MOSFET has a Breakdown Drain to Source voltage $V_{DS,br}$ of 40 V and a Continuous Drain Current I_D, max of 164 A maximum value. Obviously this transistor is a bit oversized for the work it could do but it is chosen to be sure that the MOSFET did not break during the experiment.

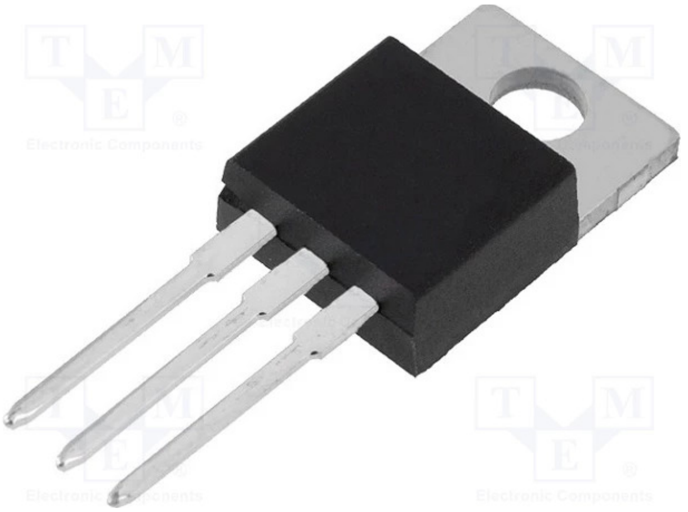


Figure 2.17: MOSFET IRL40B215

2. one diode, as in Fig.2.18 with an anti parallel connection to the solenoid valve. As long as an solenoid valve could be seen as a solenoid, it is mandatory to put an anti-jamming device to limit the value of overvoltages. The inductance of the solenoid valves accumulates energy during the current increase phase: when the current decreases, the coil generates an induced counter electromotive force F_{cem}, returning the accumulated energy to the circuit, which causes electric arcs on the contacts placed in series to the coil. To remedy this phenomenon, a reversely polarized diode is placed in parallel with the coil (anti parallel connection) during the normal power phase of the coil; at the instant of opening of the contact, the counter electromotive force that is generated has the opposite polarity to the previous one, therefore capable of directly polarizing the diode which, by entering into conduction, limits the amplitude of the overvoltage. The current circulates until the energy accumulated by the inductance is completely exhausted which, therefore, is all dissipated on itself.

Figure 2.18: Diode 1N4001

3. two resistors, one of 100 Ω and the other of 1000 Ω in Fig.2.19 with a 0.25 power rated. The 100 Ω resistor is connected between the Gate of the MOSFET and the digital pin of the ArduinoUNO to protect the pin of the Arduino, while the 1000 resistor is connected between the Gate of the MOSFET and the ground to turn off the MOSFET instantly. Without this resistor, the MOSFET continues to allow the current flow and the solenoid valve keeps open.

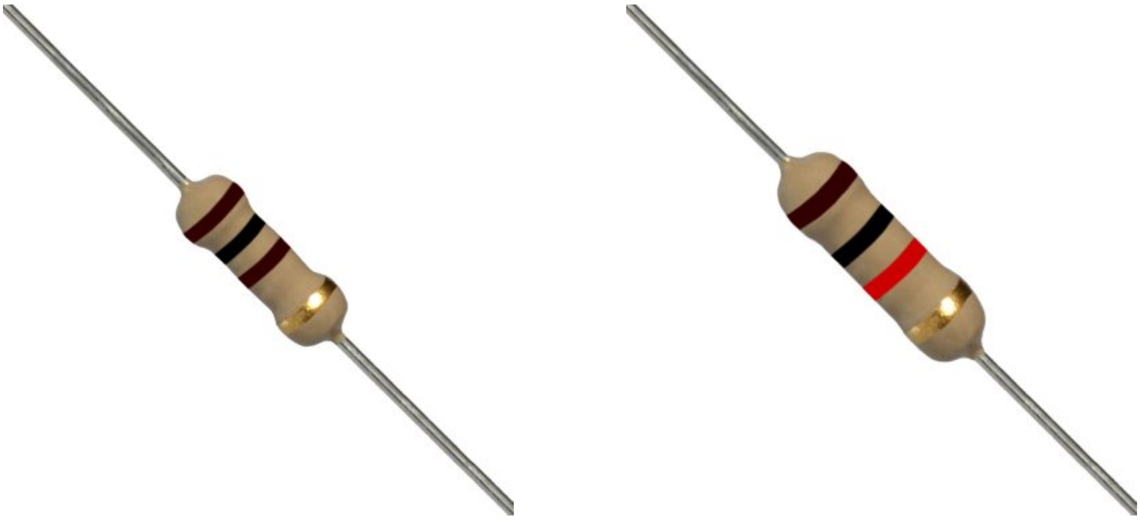


Figure 2.19: Resistors: 100Ohms on the left, 1000Ohms on the right

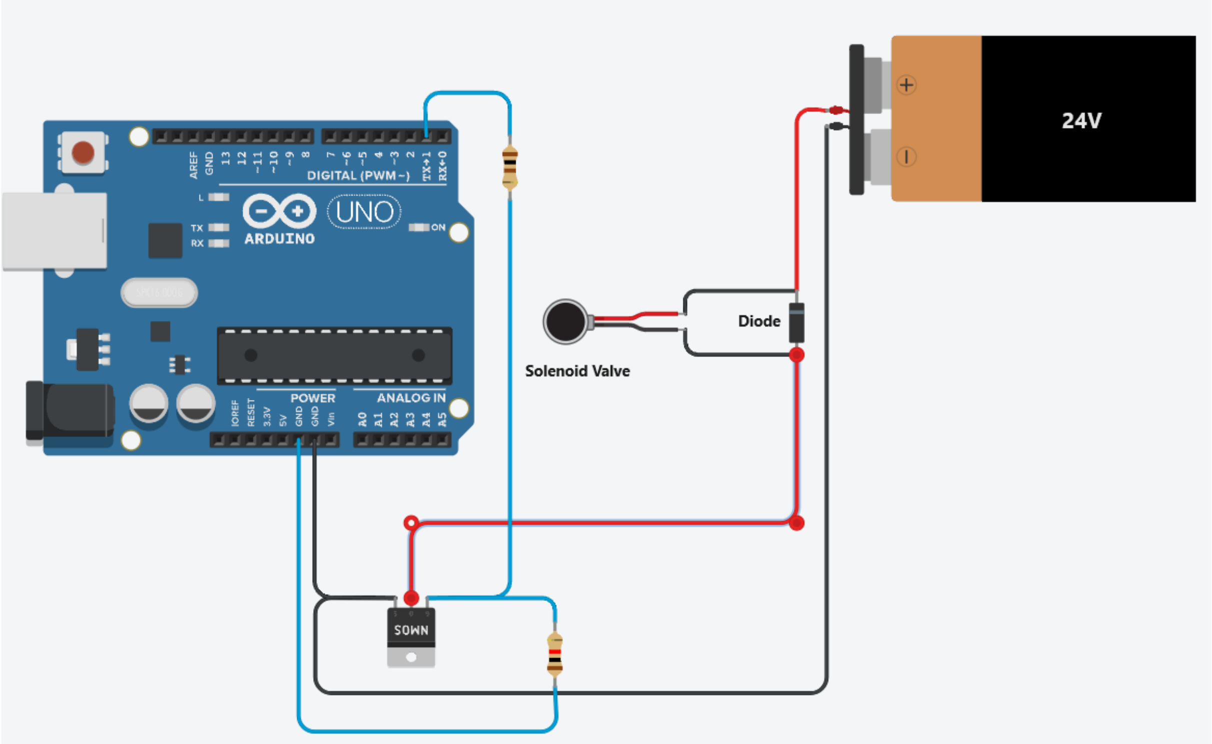


Figure 2.20: Diagram of MOSFET configuration

The tool used for the design is EasyEDA which allowed an easy and fast creation of the schematic, in Fig.2.21, the PCB in Fig.2.22 and the 3D model in Fig.2.23 of the E/E system of the Chaser.

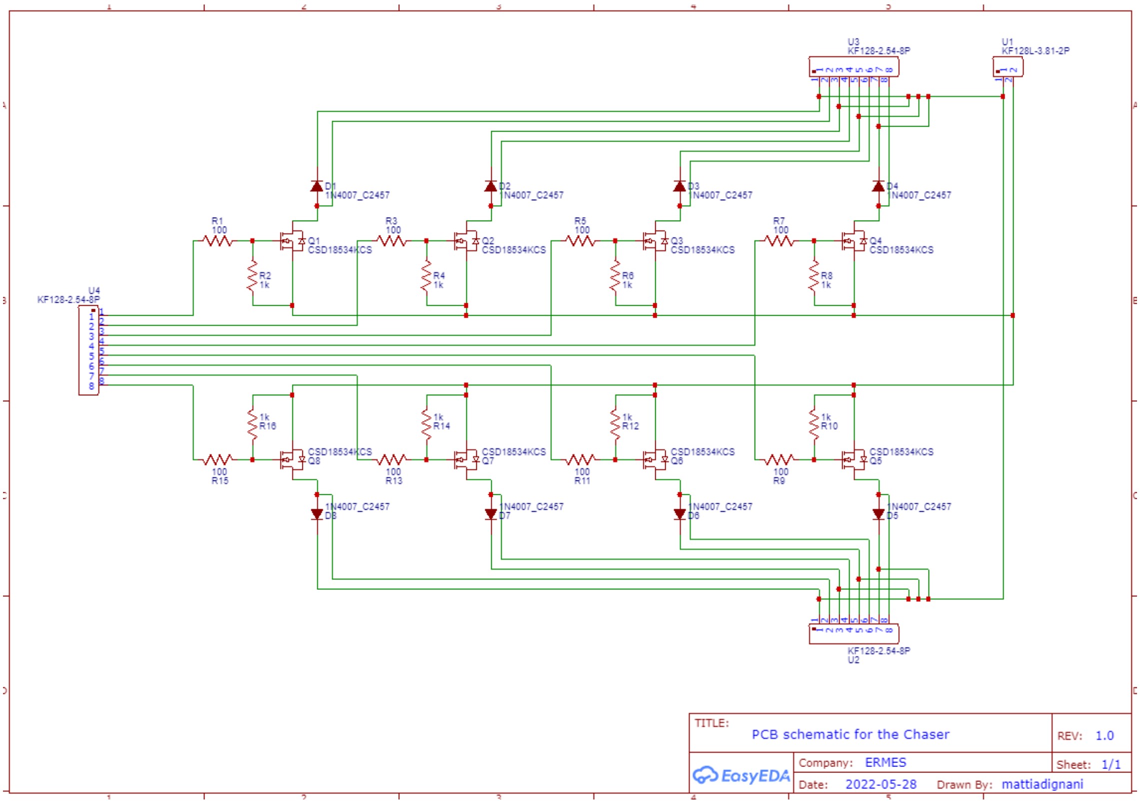


Figure 2.21: E/E schematic of the Chaser

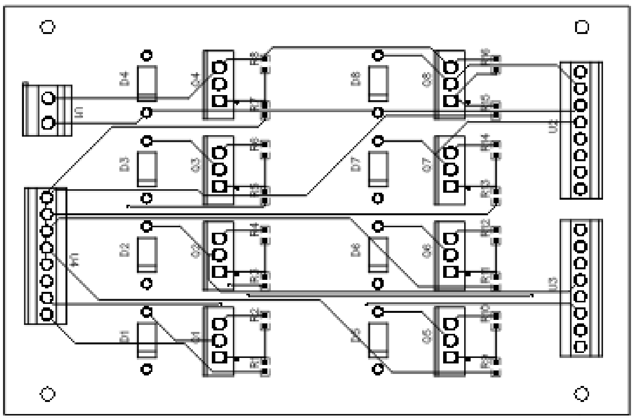


Figure 2.22: PCB of the Chaser

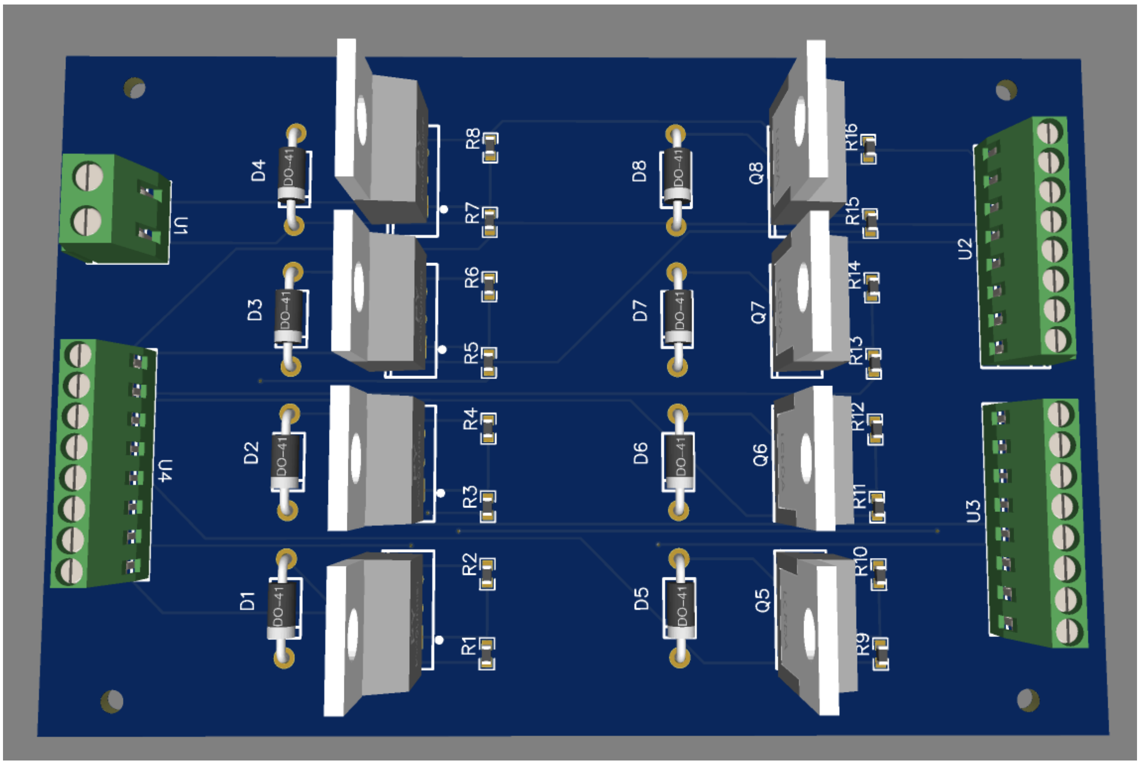


Figure 2.23: 3D model of PCB

2.1.4 Power budget and battery design

The battery was the last component chosen to complete the E/E system. First, it was necessary to make a power budget, that is power utilisation and consumption calculation associated with a system, as mentioned before. This analysis informs the actual total power consumption of the system and it is possible to choose eventual regulators to supply the subsystems and choose the correctly power supply. The components which needs a direct supply from the battery are the eight solenoid valves and the Raspberry, feeding in turn the two Arduino boards. The problem is the incongruity between the supply of the solenoid valves and the Raspberry: the solenoid valves need 24 V and 165 mA [7], while the Raspberry needs 5 V and 3 A [16]. Due to the different power supply requirements of the solenoid valves and the Raspberry Pi4, two equivalent loads could be seen in the system, one for the On Board Computer System (OBCS, composed by the two Arduino boards, the Raspberry Pi4 and the sensors), and one for the actuator part (eight solenoid valves):

- the equivalent load of the on board computer system has the same power supply requirements of the Raspberry Pi4 (5 V, 3 A). In turn, the main board feeds the two Arduino and the sensors, representing its load.

Components	Voltage [V]	Current [A]	Power [W]
RaspberryPi4	5	3	15
PiCam	3.3	0.4	1.32
ArduinoNANO	5	0.25	0.095
ArduinoUNO	5	0.5	2.5
Multiplexer	5	100	0.5
ToF	3	14	42
Solenoid valve	24	0.165	3.96

Table 2.2: Chaser Power Budget

- for the actuator part, the solenoid valves must be connected in parallel to the power supply: in this way the power supply feeds 24 V and 165 mA per each electrovales. So in total the power supply needs to deliver 24 V and 1.32 A in total.

Now that there is an approximation of the power supply of the E/E system, it is possible to study what battery could be used. The table 2.5 resumes the power budget of the Chaser.

The type of battery was chosen following the requirements in the guidelines [15]: the Nickel-Metal Hydride (NiMh) is the best match for the experiment because it is not forbidden in free floating objects (like Cubesat), it does not catch fire when, for example, it is subjected to reverse polarity and it is rechargeable. The NiMh battery cell [18] chosen is an AA battery with 1.2 V of voltage, 2100 mAh of nominal capacity and a continuous discharge current of 5000 mA, showing a C-rate of 2C, which meets the current requirements of the system (0.165 A × 8 + 3 A = 4.32 A). There are four solenoid valves that can work simultaneously and depends on the direction the Chaser should do, so the battery pack never supplies 4.32 A, but at least 3.66 A (3 A + 0.165 A × 4). The following step was to understand how many batteries the system needs to be supplied correctly and their connection, in series or in parallel. A good solution to match the voltages between the solenoid valves and the Raspberry is to connect in series ten NiMh batteries, creating a battery pack, in order to increase the voltage from 1.2 V, the voltage of one cell, to 12 V and use two type of regulators:

Regulator	V_in $[V]$	I_in $[A]$	V_out $[V]$	I_out $[A]$
Buck	12	1,95	5	4
Boost	12	1	24	0.833

Table 2.3: Buck and Boost converter values

Components	Input connection	AWG	Notes
Buck Converter	Battery pack	24	
Boost Converter	Battery Pack	22	-
Break Out Board	Buck Converter	22	-
Raspberry Pi4	Break Out Board	-	USB type C cable used
Pi camera	Raspberri Pi4	-	Flex cabled used
Arduino UNO	Raspberri Pi4	-	USB type B cable used
Arduino NANO	Raspberri Pi4	-	micro USB cable used
ToF	Multiplexer	30	
Mosfet	ArduinoUNO	30	to the Gate of MOSFET
solenoid valves	Boost Converter	26	-

Table 2.4: Wiring of the Chaser

- a buck converter: the battery pack is connected to the input of the converter which decrease the input voltage from 12 V to 5 V in order to supply correctly the Raspberry Pi4 at the output.
- a boost converter: the battery pack is connected to the input of the converter which increase the input voltage from 12 V to 24 V in order to supply correctly the eight solenoid valves at the output.

The values of both regulators from the datasheet[9] are resumed in the following table: The battery with the converters represents the power supply part of the E/E system of the Chaser. In the end, the table 2.4 resumes the wiring of one component at input and the wire used. It is important to choose the wire that fits with the voltage and current values to avoid any type of risk, so the wires chosen are over-sized and they can sustain more current.

2.2 Target

The Target is the CubeSat mock-up which has the 'cooperative' role to keep its position during the experiment and to wait the docking with the 'active' mock-up, the Chaser. It is a 1-unit CubeSat which has the dimensions of $100x100x100mm$ and it has an electric and electronic system composed by one board collaborating with a driver used to control the DC motors, shown in Fig.2.24.

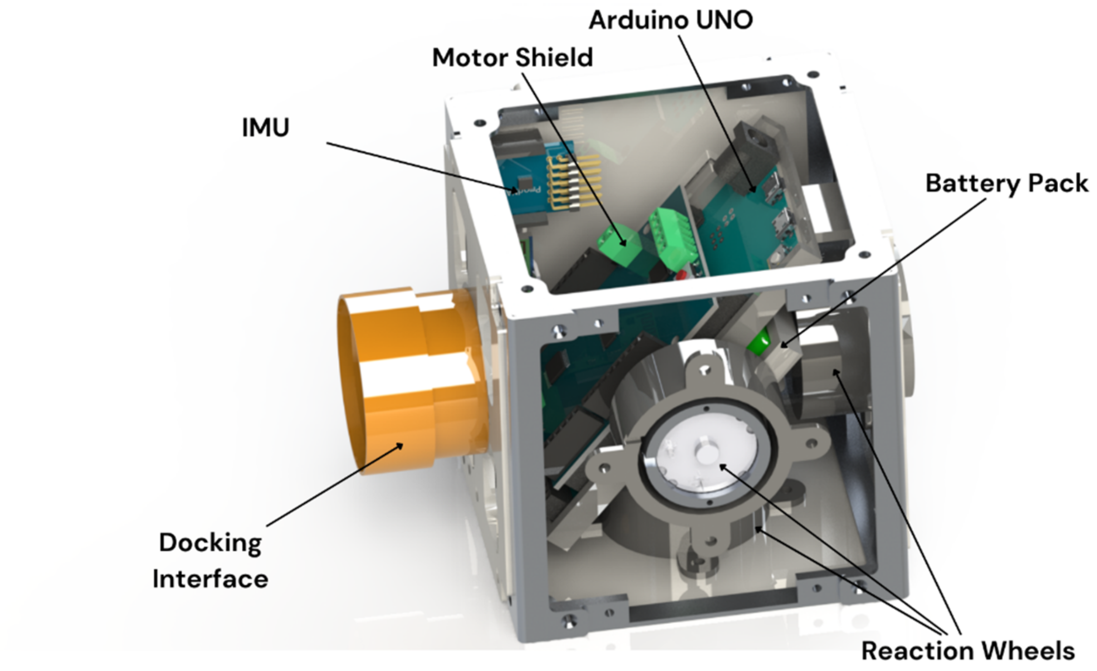


Figure 2.24: Structure of the Target

2.2.1 Electronic components

In this subsection, a list of all the components of the Target will be provided.

1. The battery pack is the *RS PRO 6V Rechargeable Battery Pack* [19]. It is composed by 5 Nimh cells which provide a voltage of 6 V, a capacity of 2 Ah and a maximum discharge current of 2 Ah. As for the Chaser, there is a switch to turn on and off the battery, the display to check the battery voltage, and a 2A fuse to protect the system.

Figure 2.25: 6V battery pack

2. The Arduino MEGA is used to compute the commands to control the three reacion wheels by analysing the data from the IMU. It is directly connected to the Motor shield used to facilitate the control of the motors.

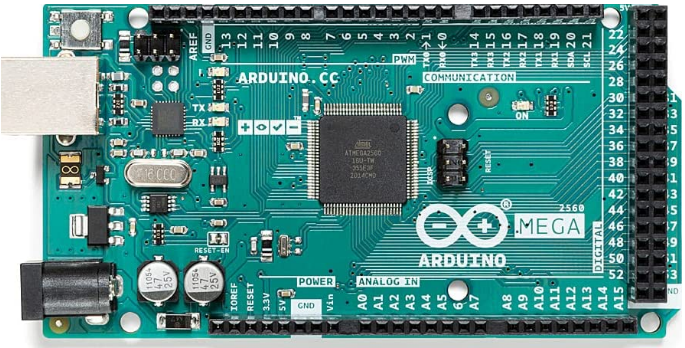


Figure 2.26: Arduino MEGA

3. The *Adafruit Motor Shield V2* [3] is the board that communicates with the three DC motors and basically controls them following the commands from the Arduino MEGA. The Arduino MEGA takes the information about the position of the Chaser from IMU and brings it to Motor Shield that manages the three DC motor to keep it stable and with a fixed attitude counteracting any disturbance. As said before, Motor Shield is plugged-in into Arduino MEGA.

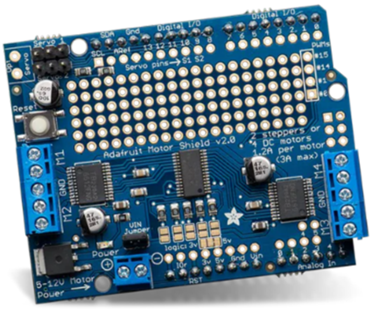


Figure 2.27: Motor Shield

4. The IMU is the *Pmod NAV 9-axis IMU* [17][10]. The IMU is connected in a feedback loop with the Arduino MEGA because it is necessary to stabilize and to keep the position of the Target during the experiment. The Arduino MEGA receives the data of position and the driver controls the reaction wheels removing the angular momentum of the Target and contrasting unwanted attitude disturbances.

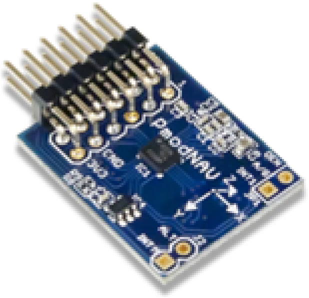


Figure 2.28: IMU

5. The Brushless DC Motors are the *Faulhaber Flat DC micromotors series 2607 SR*"[12]. There are three of them and they control three reaction wheels allowing the Chaser to rotate and to keep its position fixed.

Figure 2.29: DC motor

2.2.2 E/E system

In the Fig.2.30, there is the E/E system of the Target.

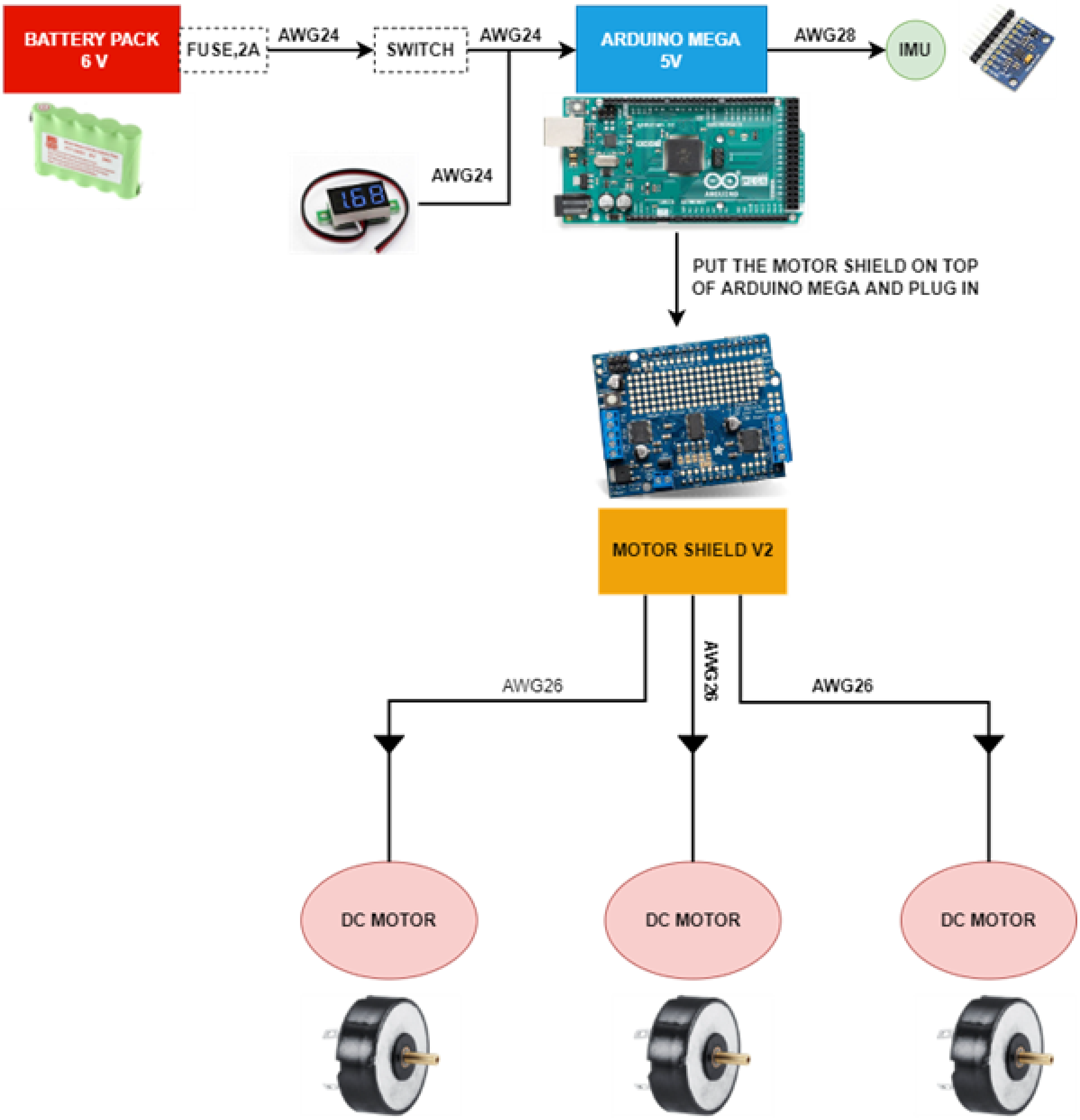


Figure 2.30: E/E system schematic of the Target

The Target has a smaller and less complex E/E system than the Chaser. It is equipped with three reaction wheel (RW) composed by a flat brushless DC motor and a flywheel. By rotating the flywheel, the satellite will rotate proportionally in the opposite direction so as to keep the angular momentum of the system constant; once the desired orientation is reached, the flywheel is stopped and the rotation of the satellite ceases. The reaction wheels themselves are normally stationary and they are only activated when it is necessary to vary the attitude of the satellite

Components	Voltage $[V]$	Current $[mA]$	Power $[W]$
Arduino MEGA	5	200	1
Motor Shield	5	1250	6
IMU	5	0.03	0.00015
Dc motor	6	400	2.4

Table 2.5: Chaser Power Budget

[2]. There are 3 reaction wheels to have a good gyroscopic rigidity on the three axis. The control of the RWs is allowed by the main board, the Arduino MEGA, which get the data from the Inertial Control Unit (IMU) about the initial position of the Target and the Arduino Motor Shield, plugged into the Arduino MEGA, which work as a driver. The collaboration between the Arduino MEGA, the IMU and the Motor Shield could be seen as a control system as in Fig.2.31, a scheme on MATLAB/Simulink used to test the RWs along yaw axes. Then a derived control system, that is comprehensive of all three axes, yaw, pitch and roll, has been coded to run on the Arduino.

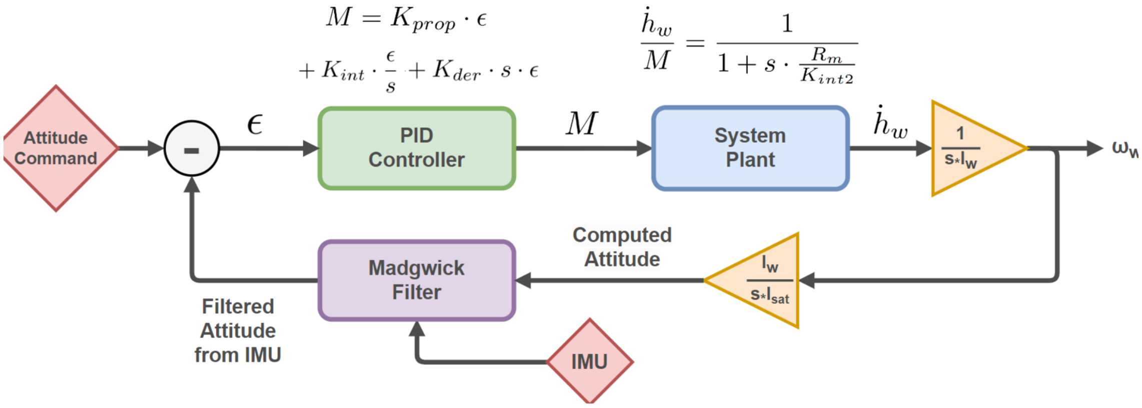


Figure 2.31: Target control system

2.2.3 Power budget and battery design

The components which need a direct supply from the battery are the Arduino MEGA and the Arduino motor shield, feeding in turn the three reaction wheels. The battery pack feeds the board and the driver through the power supply pins (Vin, Gnd) of the Arduino MEGA: the Arduino MEGA needs 5V from the Vin pin with a maximum power consumption of 1 W, while the Arudino Motor Shield needs 5 V and 1.2 A to be correct supplied. The next table 2.5 resumes the power budget of the Target.

In the end, the table 2.6 resumes the wiring of the Target.

Components	Input connection	AWG	Notes
Arduino MEGA	Battery pack	28	To the Vin pin
IMU	Arduino MEGA	30	-
Reaction Wheel	Driver motor	28	-

Table 2.6: Wiring of the Target

2.3 Release System

The Release System is the largest part of the experiment. The structure is composed by the pushing system, which can be controlled to launch the mock-ups when the microgravity environment starts, and the holding system, which holds the mock-ups on the pushing system during the rest of the experiment. The Release system could be divided into two parts: There is one structure for each mock-up and they are facing each other. The Release System schematic is shown in Fig.2.32.

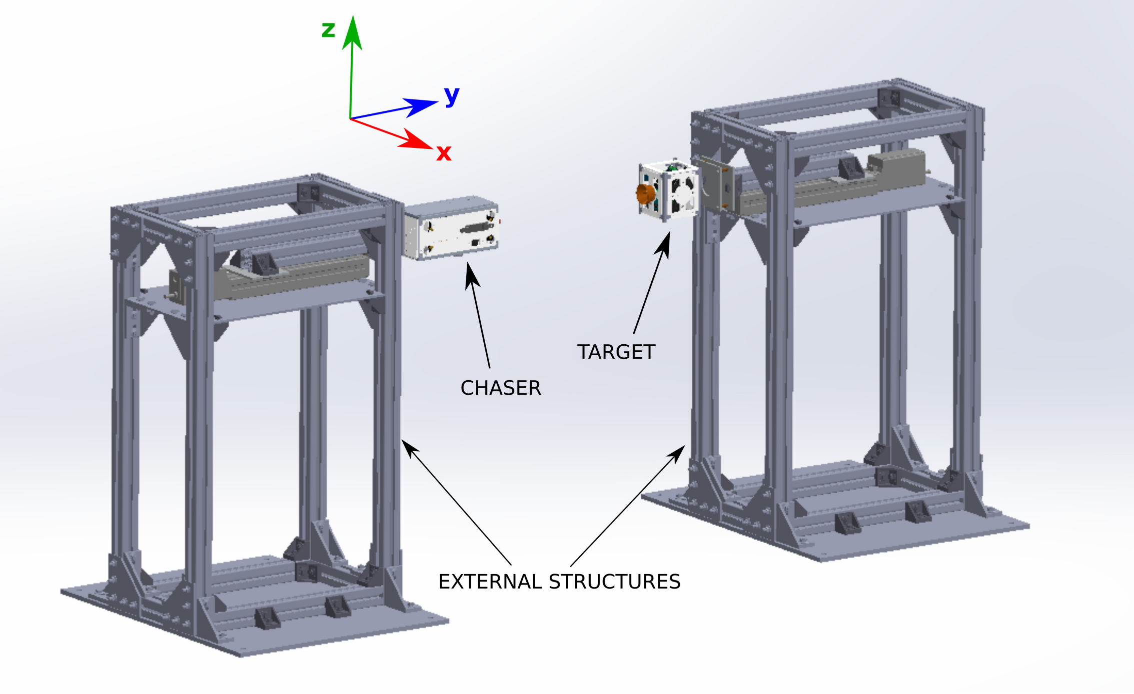


Figure 2.32: Structure design of the Release System

2.3.1 Electronic components

In this subsection, a list of the components of the Release System will be provided.

- The external structures shown in Fig.2.32 are composed by Bosch profiles and follows the Novespace Guidelines[15] on dimensions and masses.

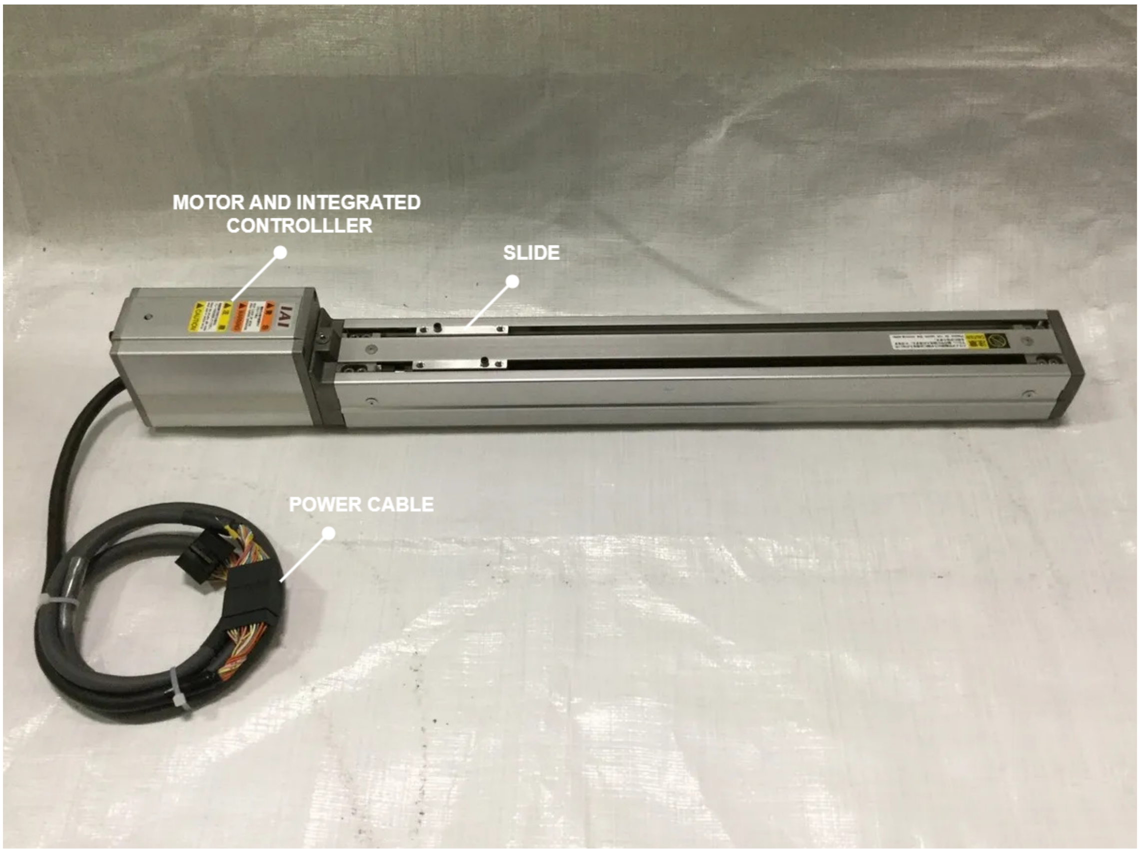


Figure 2.33: Slider IAI ERC2 SA6C

- The slider *IAI ERC2 SA6C* [20] in Fig.2.34, used to launch both the mock-ups during the experiment.
- The electromagnet *RS PRO Access control magnet* used in combination with a magnet attached to the mock-ups to keep both the Cubesat in the right position to start the experiment (see Fig.2.32).
- The Arduino MEGA, used to control the pushing and holding system during the experiment. The Arduino MEGA controls the movement of the slider for the pushing system and the electromagnet for the holding system. It is supplied by the laptop.
- Two switching power supplies, one for the slider, one for the electromagnet. For the slider, it was used a *Switching Power Supply RD-125 series*, while for

Figure 2.34: Slider IAI ERC2 SA6C

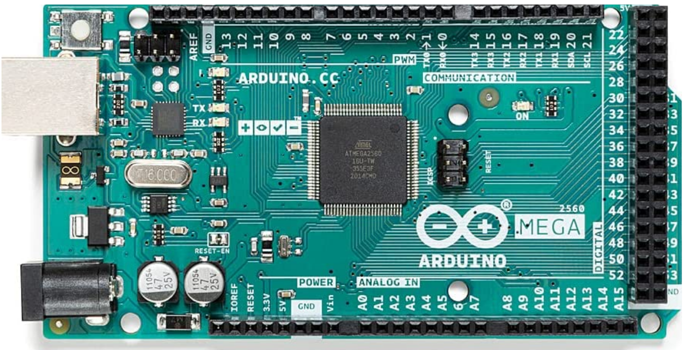


Figure 2.35: Arduino MEGA

the electromagnet it was used a *Switching Power Supply RD-65 series*. Both the electrovalves have a CEE 7/7 plug for the AC electrical socket of the airplane provided by Novespace.

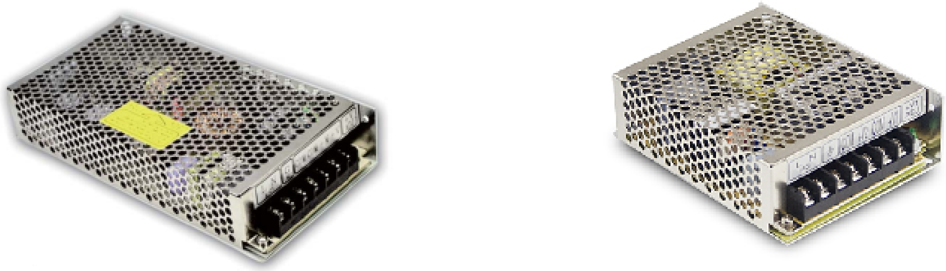


Figure 2.36: Switching power supplies for the slider (left) and electromagnets (right)

2.3.2 Pushing system

The most important component of the Release System is the slider, which represents the pushing mechanism of the release structure. From the operation manual [8], it was possible to work with the cable of the slider: it is composed by twenty other cables, eight for the power supply, ten for the pin input and output ports (PIO) and two for the serial communication (SIO), which are not used. The pins for the power supply (red) and for the control (green) of the slider used for the experiment are underlined in the connection diagram in Fig.2.38. The slider needs 24 V and 2 A to be correctly supplied. A switching power supply was selected since it was possible to use AC current provided by the airplane. It was used also another switching power supply to supply the electromagnet attached on the slider, which needs 24 V and 140 mA.

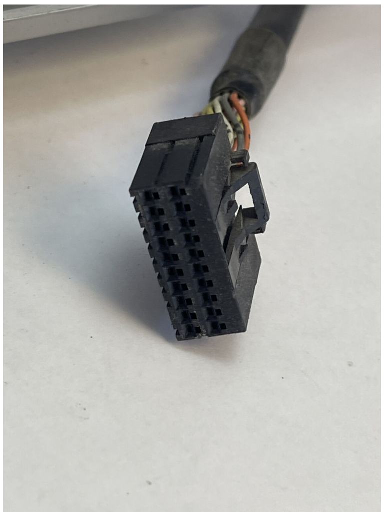


Figure 2.37: Slider cable

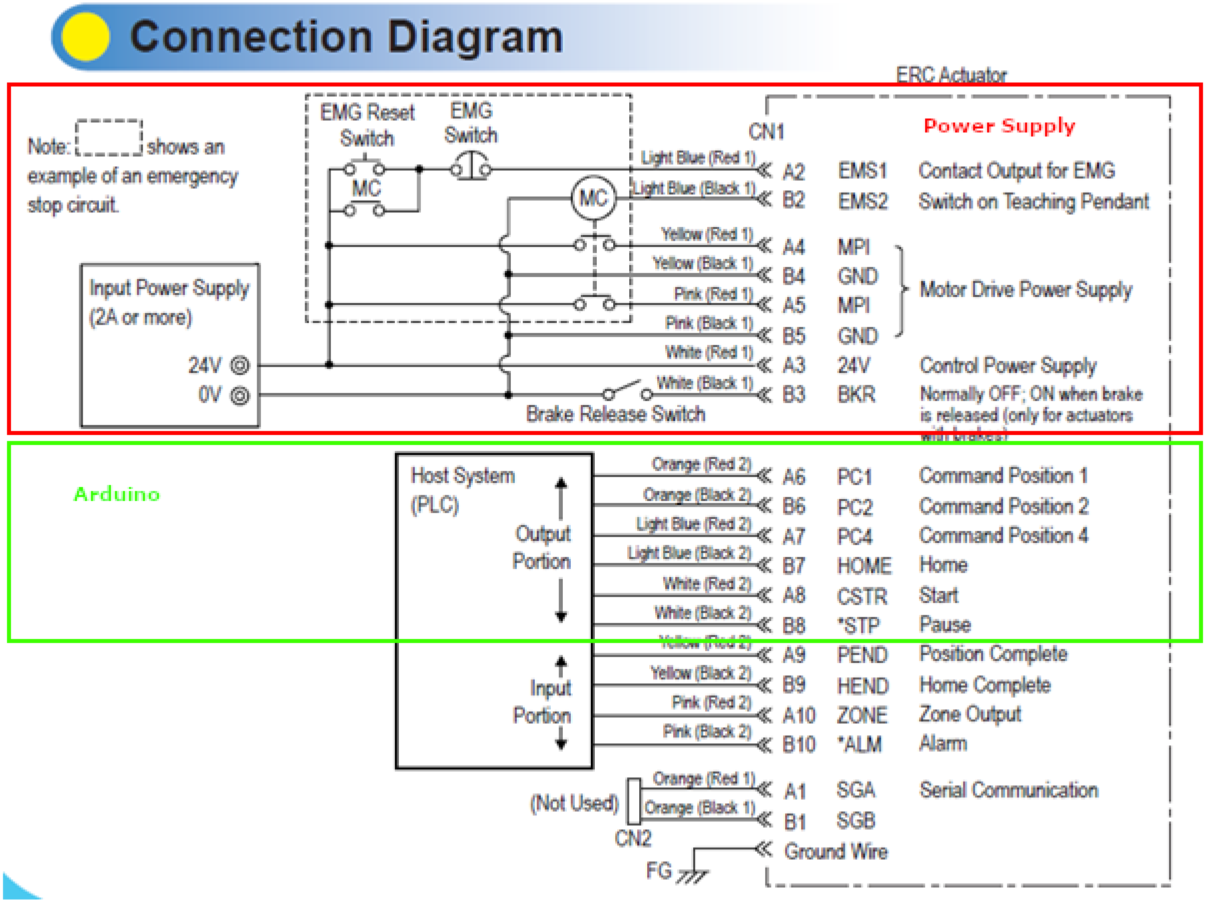


Figure 2.38: Connection diagram

2.3.3 Holding system

The holding system is composed by two electromagnets mounted on the release interface: one electromagnet is mounted on slider, the other one is on the backside of the mock-up. Moreover, it is characterized by a centering component shown in Fig.2.39 made of plastic (PLA) that extends farther than the metallic plate and get inside the upper plate of the release. The magnetic connection to the mock-ups is obtained thanks to a ferromagnetic metallic plate attached to their face (at the bottom) that acts as counterpart for the electromagnets (Fig.2.40a). This simple structure is characterized by three teeth that centre the mock-up and avoid possible rotations during the launch.

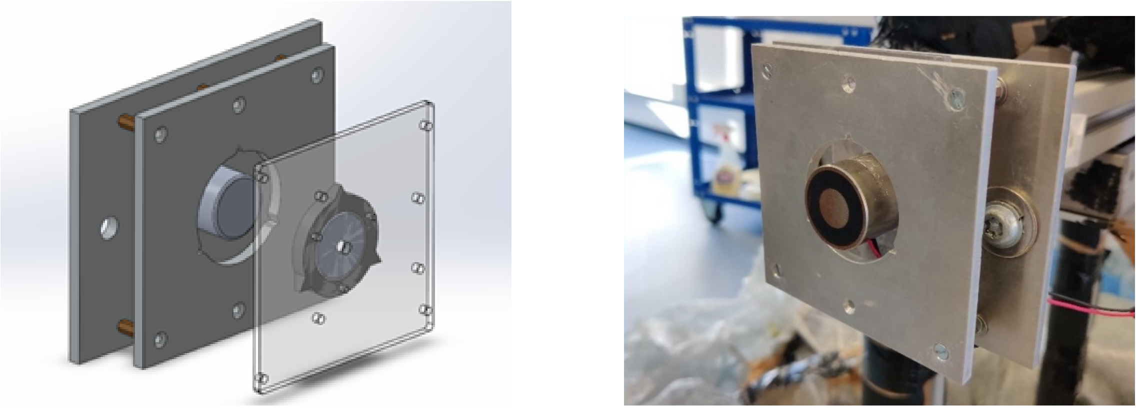


Figure 2.39: Release mechanism

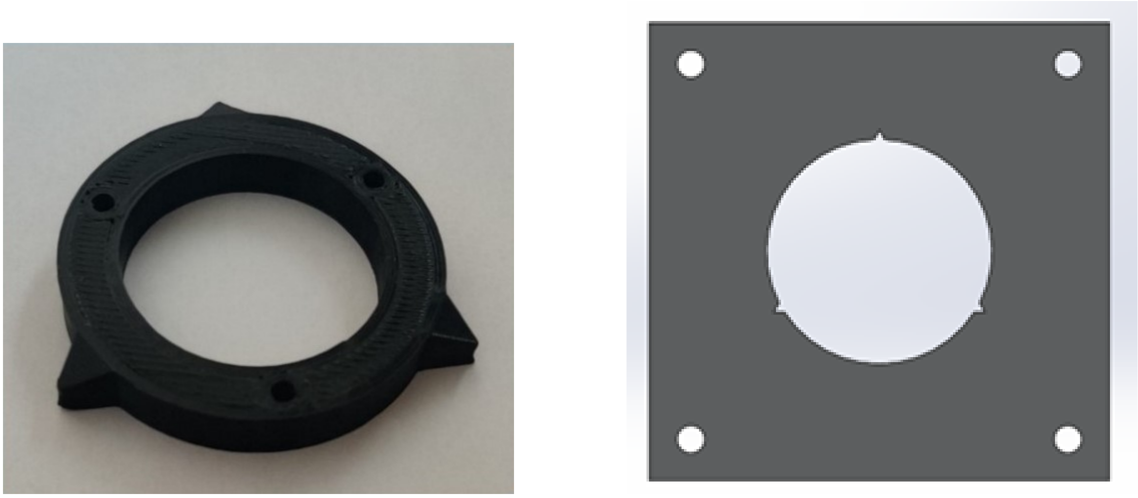

(a) Centering structure on the mock-up (b) Centering structure on the slider

Figure 2.40: Centering structure

2.3.4 E/E system and PCB design

In Fig.2.41, there is the E/E system of the Release System. The PCB is the most

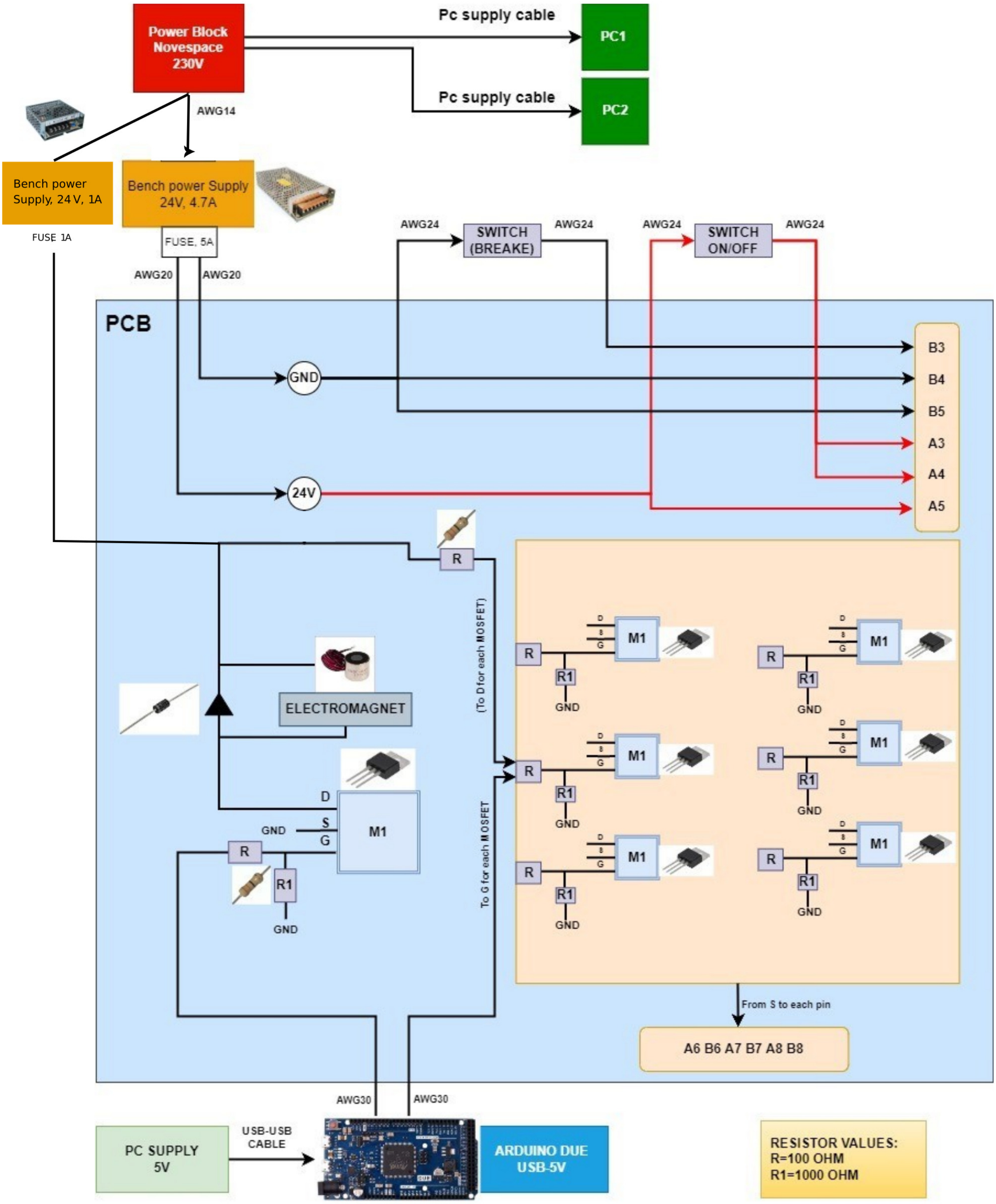


Figure 2.41: E/E system schematic of the Release System

significant part of the E/E system of the Release System, since it was implemented to control the position of the slider and also control the electromagnet used to attach the mock-ups to the pushing system. In Fig.2.38, it is possible to see that the cables selected for the test and for the experiment are **Command Position 1, 2, 4, Home** and **Pause**. The **Command Position** allows the slider to reach different positions, **Home** is for the return in the initial position and **Pause** cable to stop the slider at a certain position. Each position cable could be seen as a load. When the slider was studied and tested, it was seen that when a command cable was grounded, for example the Command Position 1, the slider moved to the corresponding position. In this way, a p-type MOSFET configuration was chosen, where the cable was directly connected to the Source of the MOSFET, the Drain to the Ground, and the Gate to the PIO of the ArduinoMEGA: when the PIO of the Arduino was Low, the MOSFET started to conduct and the slider moves to the corrisponding position, while when the PIO is High, the MOSFET doesn't let the current to flow, and the slider keeps the position. In the next three figure, there are the schematic in Fig.2.42, the PCB in Fig.2.43 and the 3D PCB in Fig.2.44.

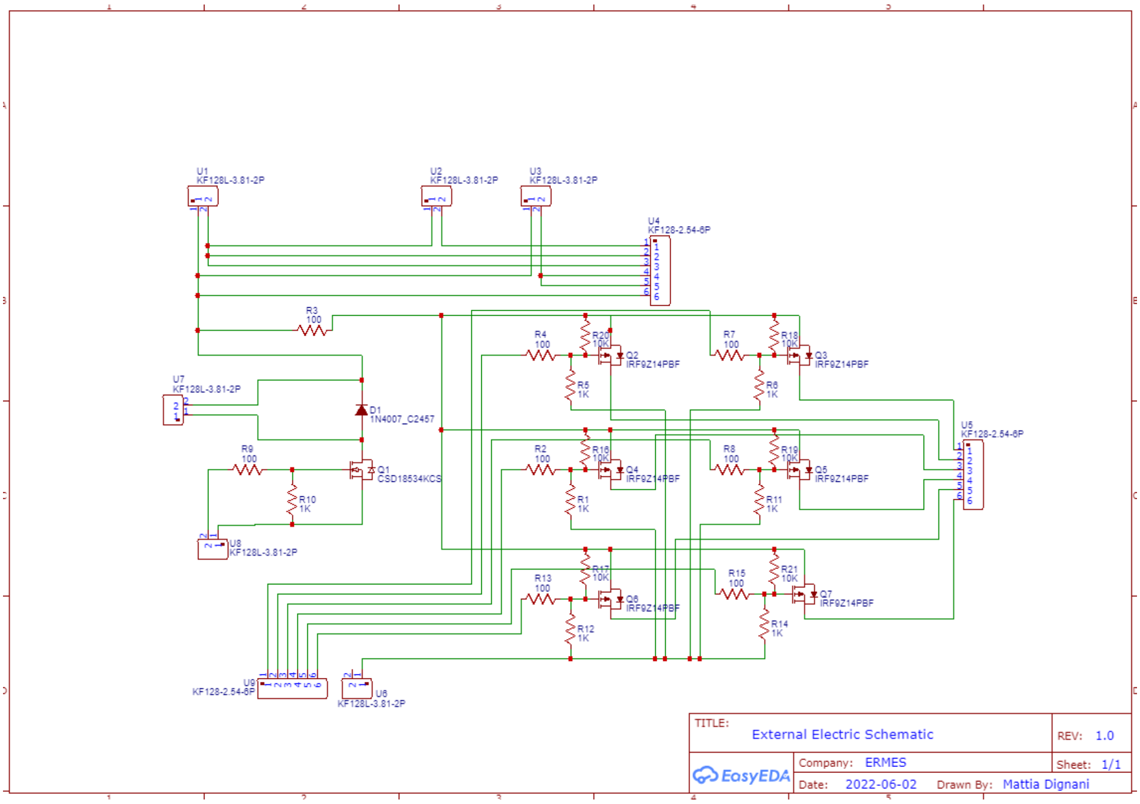


Figure 2.42: E/E Schematic of the Slider

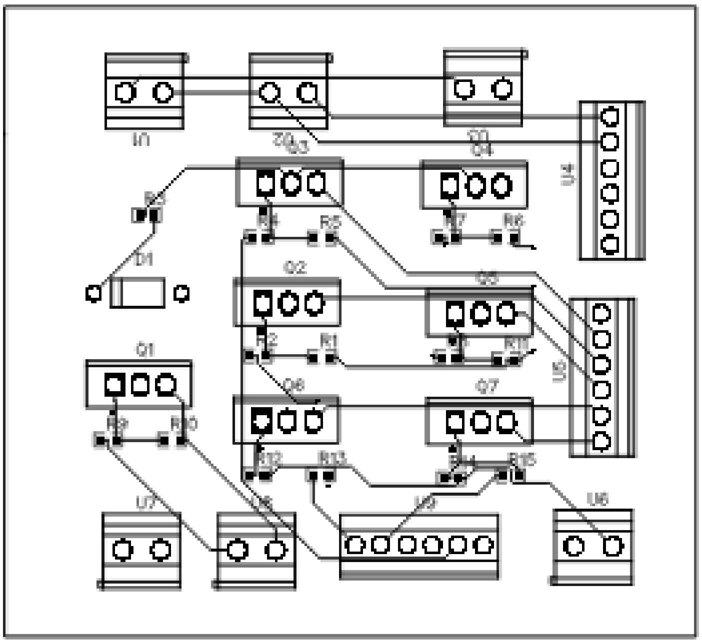


Figure 2.43: PCB of the Slider

The position cable were combined between each other to understand what movements are needed for the experiment. Two types of solutions have been implemented. The first one regards static releases, in which both mock-ups are released statically, while the second one includes pushing releases, in which the Chaser is accelerating before the magnetic disconnection, while the Target is released statically. The Fig.2.45 is the reference for the description of the type of release. The Slider initially starts at Home position and it can move up to 500mm. It and it can reach the Position 1, far 250 mm from the Home, and the Position 2, far 450 mm from the Home. The speed of the slider was programmed to be 10 mm/s or 30 mm/s. During the experiment it was decided to select the 30 mm/s speed.

- Static Release
  - Mode 1: Chaser and Target are both released at position 1, then the arms come back at Home (Position 0).
  - Mode 2: Chaser is released at position 2, while Target is at position 1, then the arms come back at Home.
  - Mode 3: Chaser and Target are both released at Position 2, then the arms come back at Home.

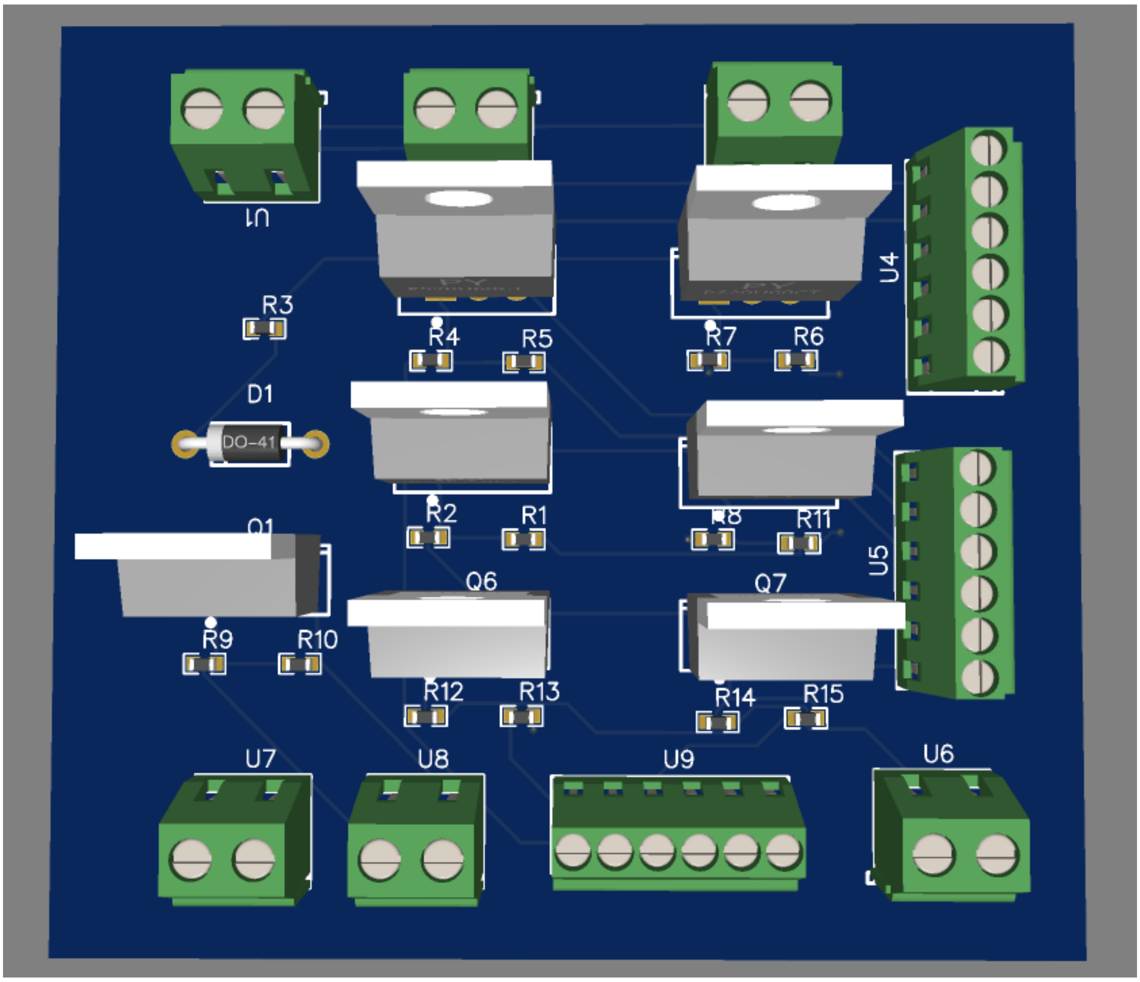


Figure 2.44: 3D model of the PCB

- Pushing Release
  - Mode 4: Chaser is accelerated and released at position 1, while the Target is released statically at position 1, then the arms come back at Home.
  - Mode 5: Chaser is accelerated and released at position 2 (same velocity of Mode 4, but closer to the Target), while the Target is released statically at position 1, then the arms come back at Home.
  - Mode 6: Chaser is accelerated and released at position 2 (same velocity of Mode 4, but closer to the Target), while the Target is released statically at position 2, then the arms come back at Home.

It is important to underline that even though each release may differ, they all last the same amount of time because the mock-ups need to be released in a precise moment. The moment of the release is chosen to be around the middle of a parabola because it is when the low gravity is at the lowest. Therefore, the release

Components	Input connection	AWG	Notes
Switching converter	AC socket	-	CEE 7/7
Slider	Switching converter	26	Power pins
Slider	Arduino MEGA	28	Control pins
Arduino MEGA	Laptop	-	USB type B cable
Electromagnet	Switching converter	28	-

Table 2.7: Wiring of the Target

happens around 8-10 s (information provided by Novespace) from the start of the low gravity phase. In fact, all releases last around those values, considering both positioning and eventual acceleration. The error between the release of the Chaser and the Target has been measured less than 1 ms. Other type of releases that are hybrids between those ones has been prepared in case of necessity.

2.3.5 Power Budget and Wiring

The Release System can be supplied by the AC current provided by the airplane, so it was decided to use switching converters to supply the electromagnets and the sliders. It was chosen for the slider *Switching Power Supply RD-125 series* for the slider. It can supply 24 V and 4.7 A and it fits with the power request of the slider: as mentioned before, one slider needs 24 V and 2 A, so the two sliders needs in total 4 A. While for the electromagnet it was chosen the *Switching Power Supply RD-65 series*. It can supply 24 V and 140 mA and it fits with the power request of the electromagnet: one electromagnets needs 24 V and 140 mA, so the two electromagnets needs in total 280 mA. The table 2.7 resumes the wiring of one component at input and the wire used.

2.3.6 Docking Interfaces

Two different configurations have been planned to be tested during the parabolic flights. In particular, the two interfaces are a probe-drogue configuration and an androgynous configuration. The two configurations differ in geometry but have few features in common in terms of the type of connection post docking and in terms of solution for the design in view of facilitating the manoeuvre.

The connection between the two mock-ups is granted thanks to a small permanent magnet placed on the Chaser This magnet attaches to a ferromagnetic counterpart on the Target. Initially, both docking interfaces had been designed with a mechanical connection. The connection was obtained through a rotating component which would have locked the two interfaces. However, it has been replaced

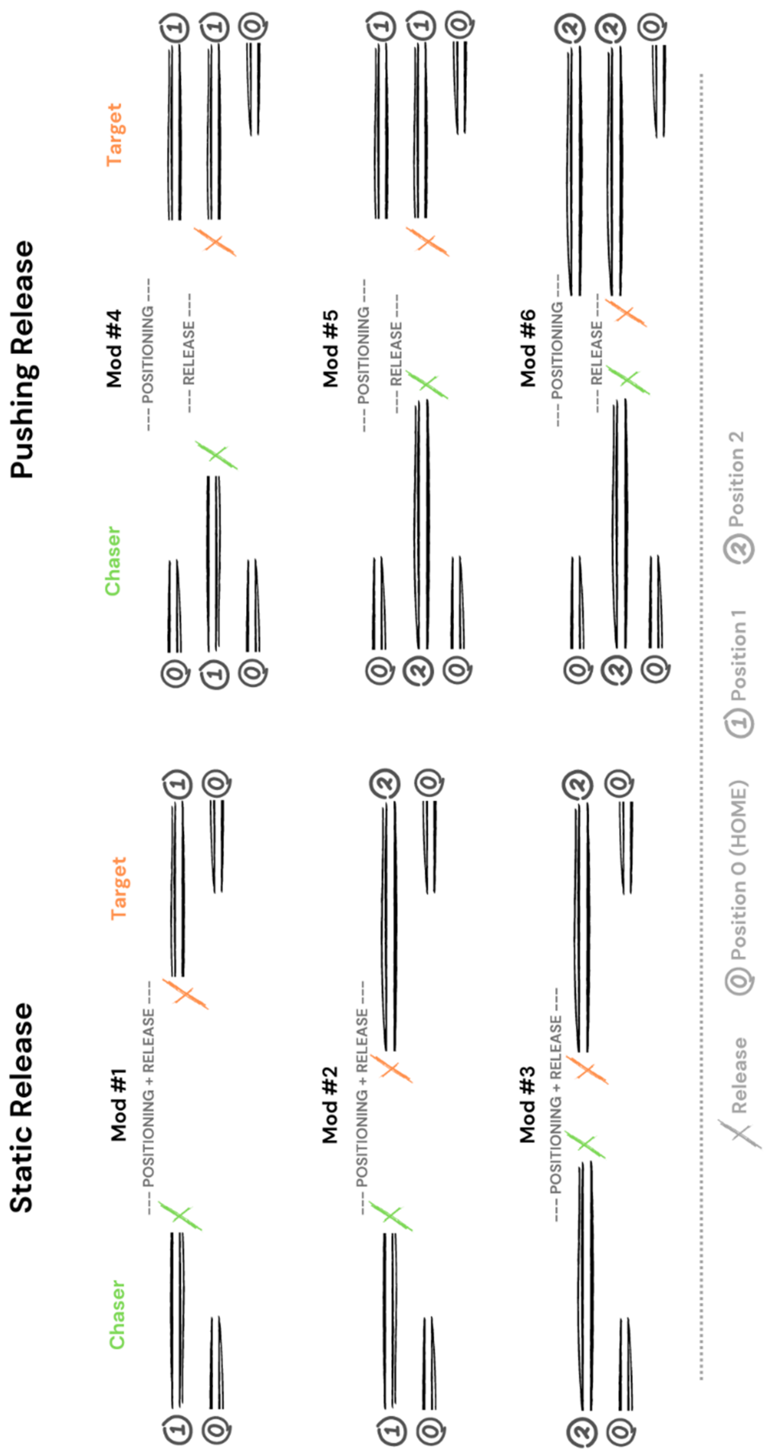


Figure 2.45: Release modes

by a magnetic constraint because of risks and hazards analysis. In fact, the shaft of the servomotor used to rotate the mechanical locking components could have been severely damaged if hit directly, or just by falling during the hyper-gravity phase. Therefore, in accordance with the Novespace Guidelines, it has been replaced with a non-mechanical one.
The probe-drogue configuration is characterized by a probe on the Chaser and a drogue on the Target. The shape of the probe-drogue configuration facilitates the manoeuvre by permitting a sliding motion of the two interfaces in order to better align the two mock-ups. The probe-drogue miniaturized docking interface is shown in 2.46. The difference between the probe-drogue configuration used in ERMES and the one described in ([5]) is the above-mentioned magnetic constraint, in fact the tip of the probe has been replaced with a small magnet, in order to move from an active mechanical docking to a passive soft docking solution.

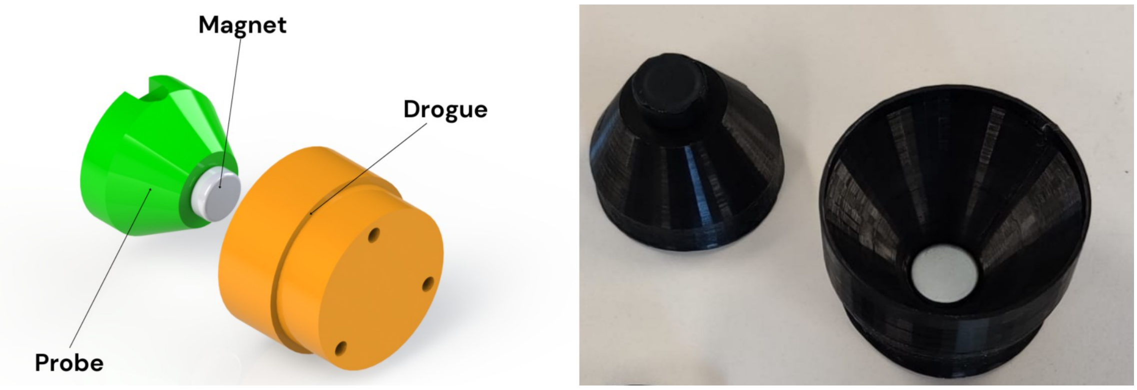


Figure 2.46: Probe-Drogue docking interface

Whereas in the androgynous configuration (shown in figure 2.47.) the docking interface is symmetric, therefore it is the same for both Chaser and Target. The connection between the mock-ups is achieved thanks to the magnet and its counterpart, which are both placed at the centre of the interface. This configuration too has been designed to have a shape that helps the docking by auto-centring the interfaces.

2.4 Setup on the airplane

The cabin layout in Fig.2.48a is composed by two Racks, the net and the base plate. The Racks 1 and 2 represents the Release System of the of the experiment, one for the Target and the other one for the Chaser, shown and explained in the previous chapter. Around the Release System there is a five side net with the

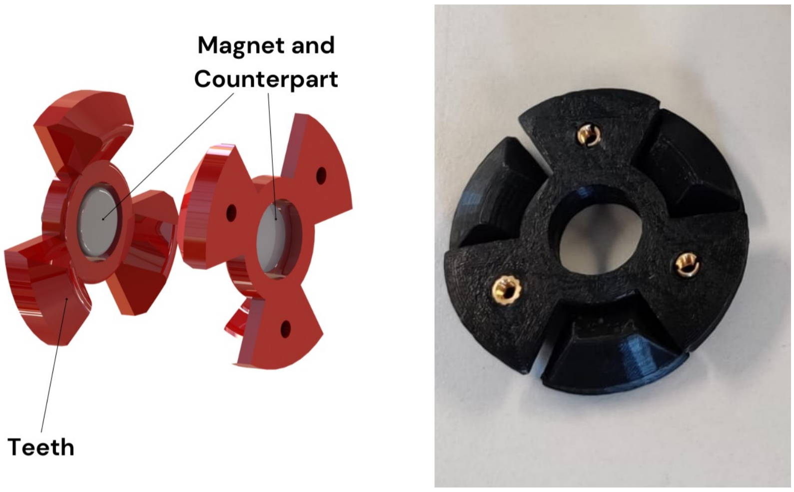
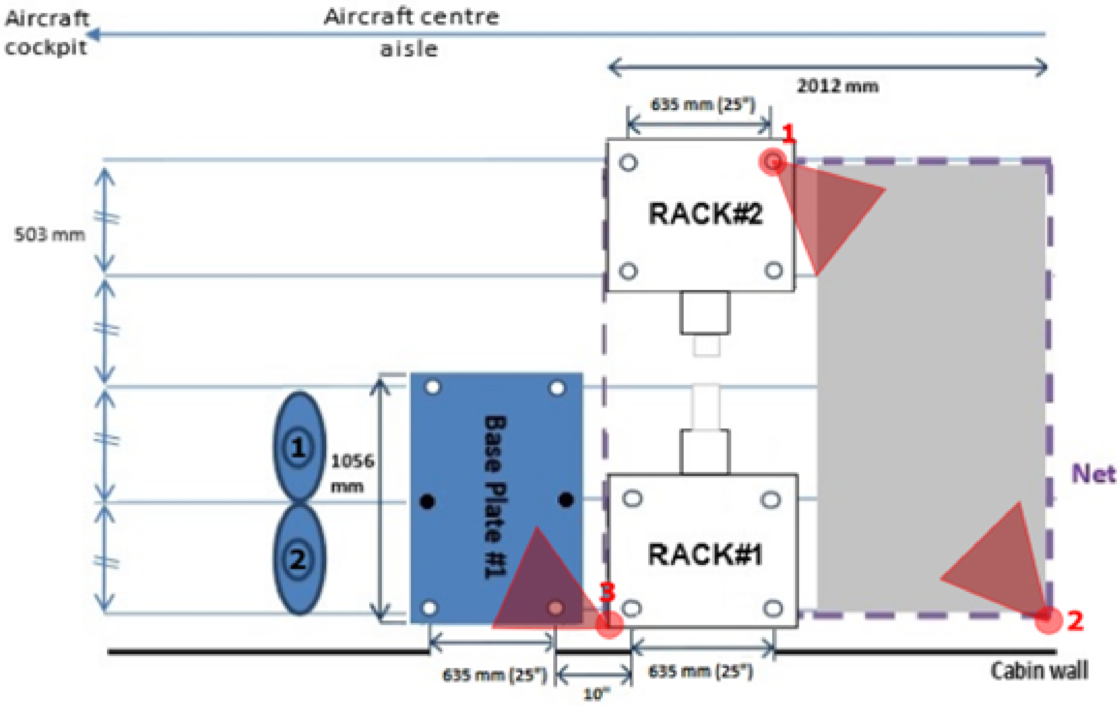
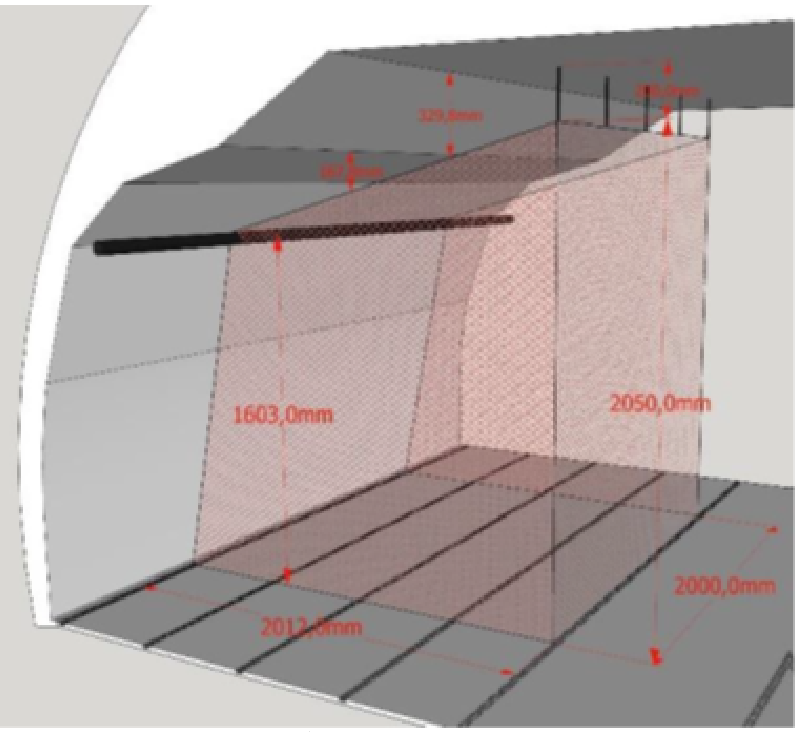


Figure 2.47: Androgynous docking interface

dimensions $2012mmx5003mm$ (Fig.2.48b). It was used to border the area and to contain both mock-ups during the micro gravity environment to avoid the free-floating of the Chaser and Target along all the airplane. In the base plate there are two computer laptops to monitor and control data got from the mock-ups, two bags dedicated to expandable components, such as for example CO2 cartridges or batteries and two electrical cabinet where there are the power supply of the Release system. Moreover, there were three cameras (the red part in Fig.2.48a) to record the experiment. The video were used to compare the performance of the mock-ups with the data got from the on board computer system of the Target and the Chaser.



(a) Cabin layout schematic



(b) Five side net

Figure 2.48: Cabin layout design

2.5 Laboratory Testing

The Laboratory Testing is a series of tests to validate singularly some aspects of Target and Chaser up to simulate the entire manoeuvre. All the tests were carried out on a low-friction table in the laboratory. In order to make the Chaser and the Target levitate over the table, sleds with flat round air bearings have been designed to hold them (see figure 2.49).
This type of test was the best solution to understand if the Chaser and the Target could have worked in the right way. It is impossible to reproduce a microgravity environment, so the low-friction table was a good test before the parabolic flight. Initially, the two mock-ups were tested separately. The tests of the Target focused on validation of attitude control, more precisely on the control of the solenoid valves and on the trajectory to follow, calculated by the Raspberry Pi4, to reach the Target. All the tests have been carried out implementing a Motion capture technology, in particular the OptiTrack technology, in order to track the mock-ups.

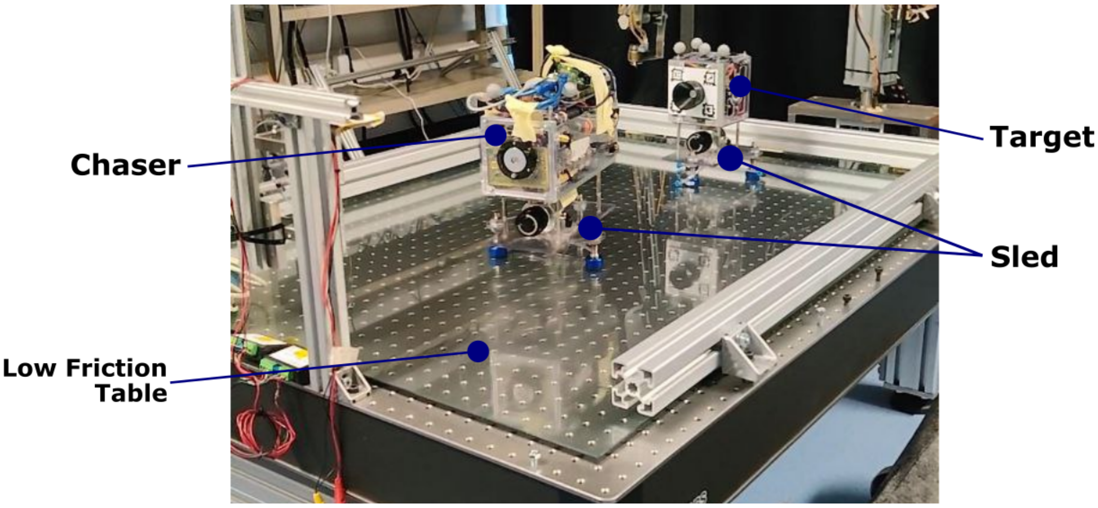


Figure 2.49: Chaser and Target on the low friction table

During the simulations of the manoeuvre, the Chaser was placed in front of the Target. As mentioned before, the aim of the Chaser is to reach the Target. Basically, these simulations aim at improving the docking manoeuvres performed by the Chaser in view of the testing on the parabolic flight. In Fig.2.50 snapshots from the video recording of a test performed on the low friction table are shown.

The graphs reported in figure 2.51 and figure 2.52 show the relative trajectory followed by the Chaser and the relative speed. The graphs shows three DoFs:

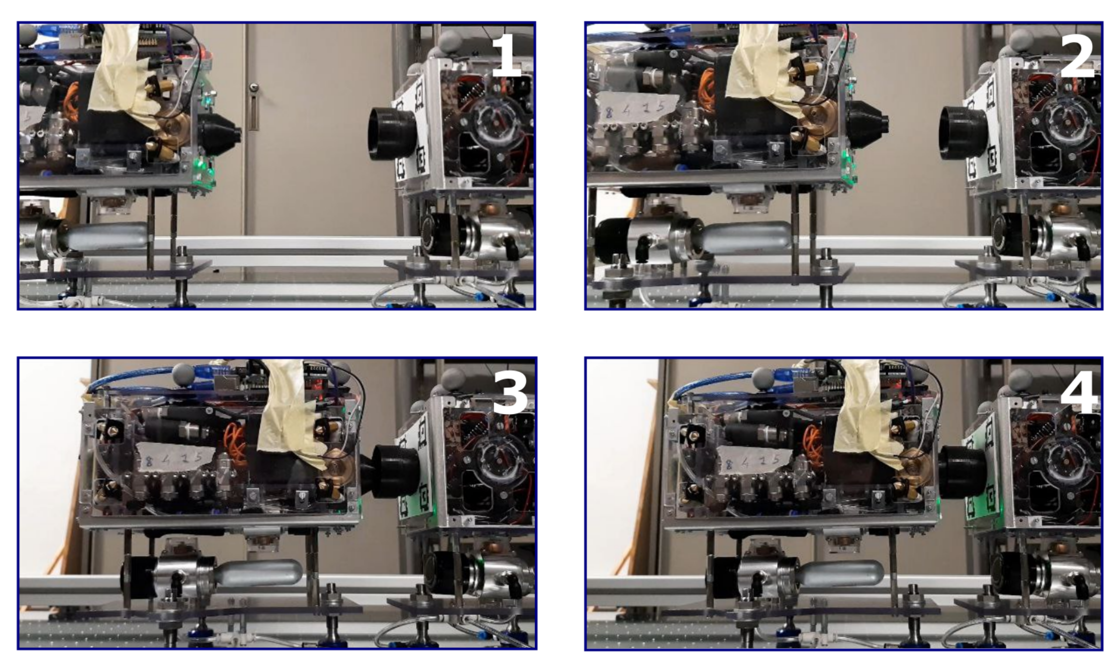


Figure 2.50: Testing on low friction table – Snapshots from the video recordings

- the trajectory along x-axis, representing distance from the Chaser and the Target;
- the trajectory along y-axis;
- the yaw, or else the rotation along the z-axis

Before discussing the results, the layout of the graphs must be described:

1. The **trajectory computed by the Chaser** is represented with a blue line with orange circles. The orange circles represent the data from the localization of the Apriltags printed on the screen and saved, while the blue line is the interpolation between them. Therefore this data takes into consideration all the calculations made by the Raspberry Pi4, elaborating the data obtained by the Pi Camera and the ToFs.

2. The **trajectory reconstructed thanks to the reference camera** is represented with a green line. The trajectory reconstruction is performed thanks to the OptiTrack for the tests in the laboratory. The importance of including these data is to validate the localization and path computation of the Chaser by introducing an external reference.

3. **The commands sent to the Arduino NANO to control the Solenoid Valves** are represented with vertical coloured dotted lines. In particular, blue dot-

ted lines indicate corrections along the positive direction of the axis (accelerations), while red dotted lines indicate corrections along the negative direction of the axis (decelerations). Moreover, the number of cycles, that is labelled alongside the dotted line, indicates the duration of the impulse.

4. The black dotted lines, instead, represent all the constraints of the software.

Regarding the duration of the manoeuvre, the tests aimed generally to have a manoeuvre of around $8s$ or fewer starting from around $300mm$ of initial face-to-face distance. The reason is that, although the low-gravity phase is theoretically longer, it is important to have margins. In the graphs is reported one such kind of test. The release has been performed manually with an initial misalignment, indeed the initial drift velocity in all three DoFs is just a consequence of the manual release. The initial misalignment (around $25mm$ for the y-axis and around 13° for the yaw) was always chosen to be near the tolerances of the software ($20mm$ for the y-axis and 12° for the yaw) because the focus was on seeing if the Chaser was able to correct it and to stabilize the approach. This method has been used also to find empirically the maximum allowable misalignment.
However, some tests were performed also with a nearly perfect alignment. In these tests, the sequence of commands sent was mainly composed of forward thrusts (positive x-axis) with a series of small adjustments in lateral misalignment and attitude. During the tests, the team understand it was better so sent commands for the control of the electrovalves with an higher frequency and a low thrust to correct the measured misalignment more frequently respect to the Target. The approaching threshold is reached at around $7s$ after the beginning of the manoeuvre. However, after around $5s$ the frequency of the commands increases even if the threshold has not been passed. The reason is because there was the necessity of stabilizing faster the y-axis. Then, after passing through it, the Chaser clearly favours attitude control over the position. The increase in the frequency of the commands during the docking phase improves the control by adding layers of precision. The results suggest the Chaser was able to correct the initial misalignment on both attitude (yaw) and position (y-axis) and simultaneously get closer to the Target. From the results of these tests, it was also possible to validate the integration of the localization system because the precision of the computed manoeuvre and the errors were acceptable to assume the success of the tests.

One final remark regarding the testing in the laboratory focuses on the simplicity of the entire system. The simplicity of the entire system was a key requirement in the design, although it was assumed that this kind of approach would have affected the efficiency. Actually, the series of tests performed in the laboratory suggests that the simplicity of the software does not impact the results deeply. Nevertheless, on several occasions, the system did not perform well while testing manoeuvres with a drastically decreased duration. In fact, if the Chaser was tested with the same initial distance but by imposing via software fast manoeuvre approaches (high initial acceleration) or by inducing a strong initial velocity (around $30mm/s \pm 15\%$), the precision of the docking clearly decreased.

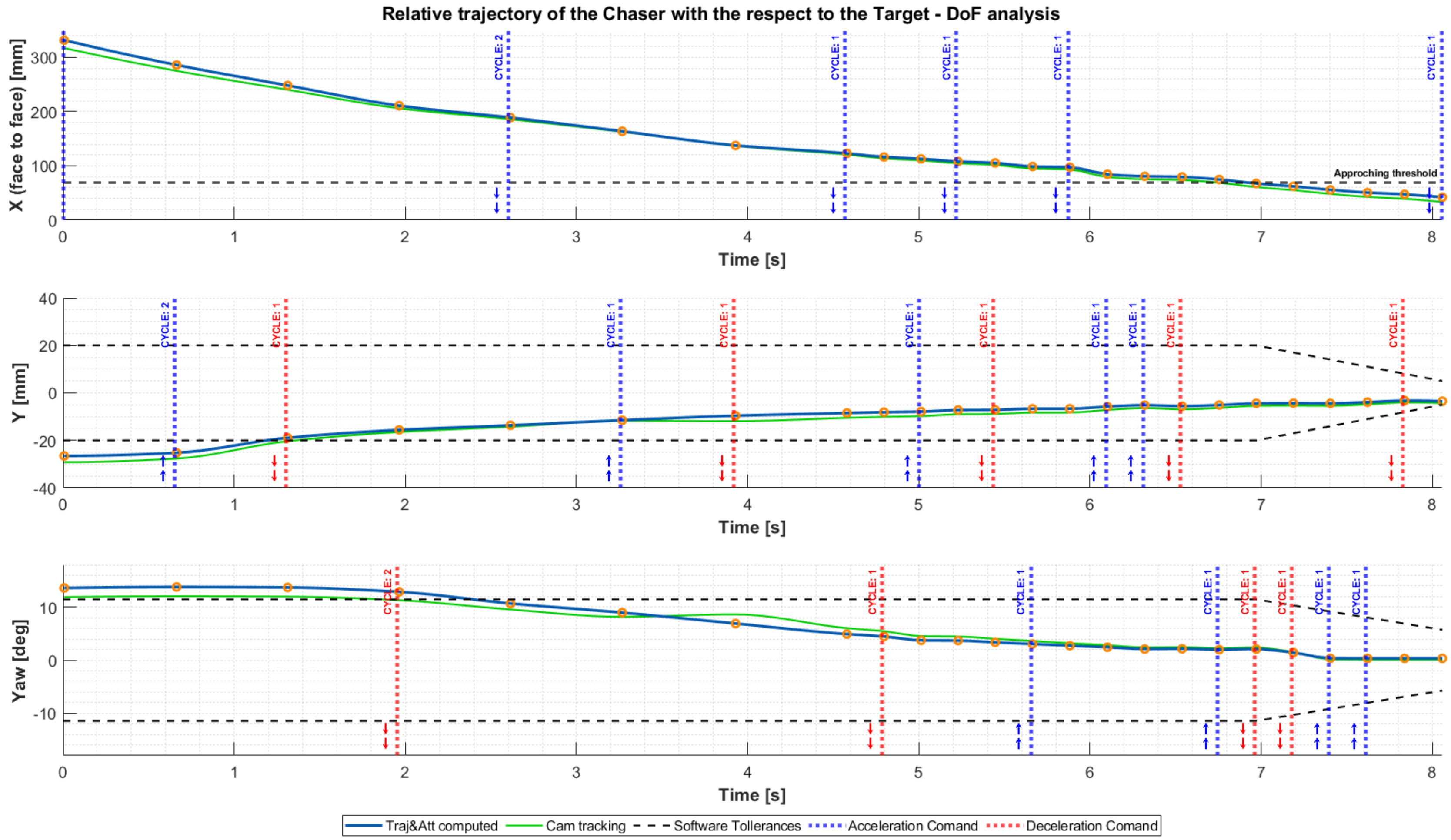


Figure 2.51: Testing on low friction table - Relative trajectory of the Chaser with the respect to the Target with reference trajectory from external camera tracking (OptiTrack)

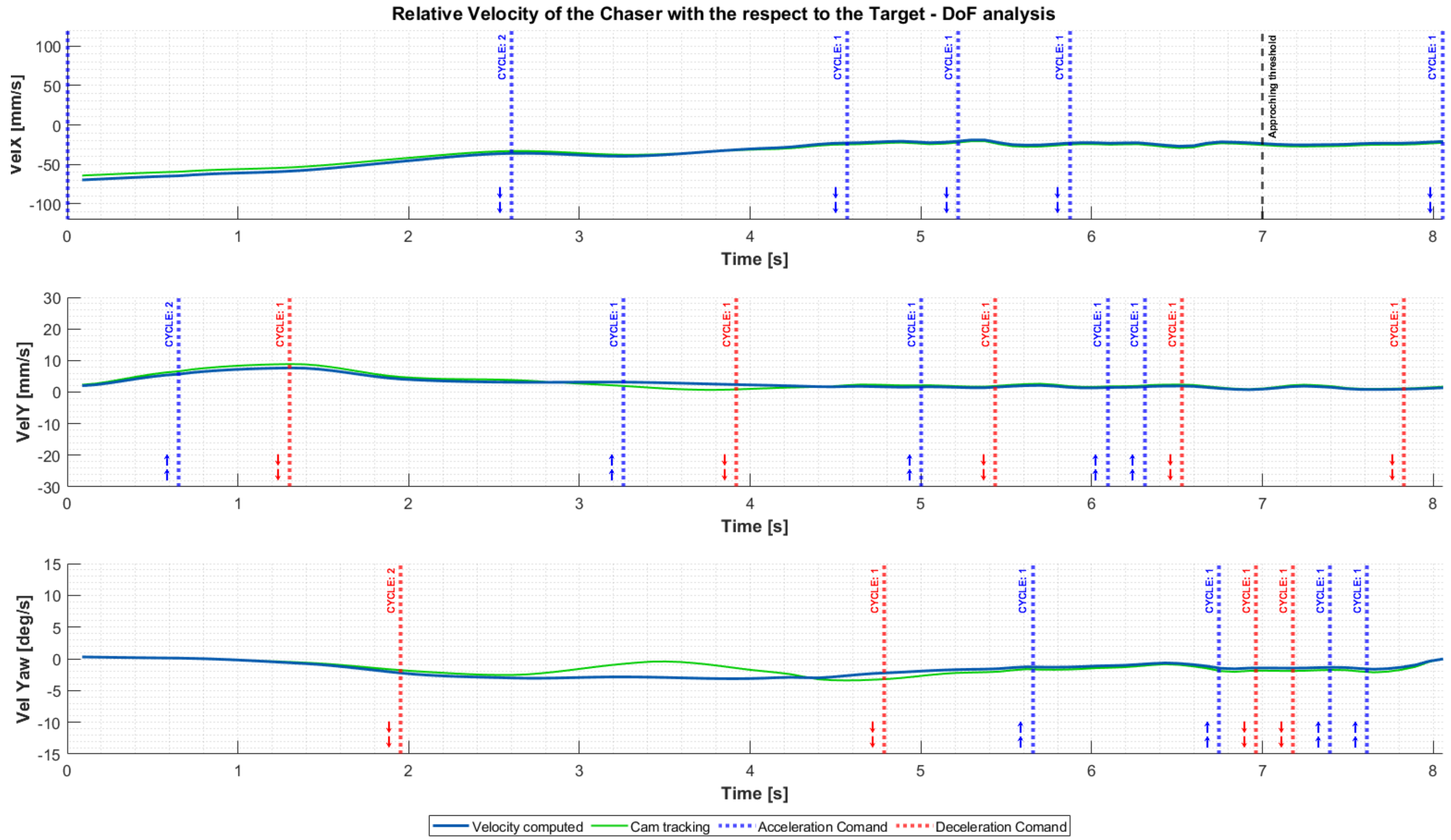


Figure 2.52: Testing on low friction table - Relative velocity of the Chaser with the respect to the Target with reference velocity from external camera tracking (OptiTrack)

Chapter 3

Parabolic Flight Campaign

In this chapter the parabolic flight campaign will be briefly explain. Moreover, at the end, there will be a report of the three days of flight and comments about the behavior of the E/E system of the Chaser, Target and Release System.

The team composed by Alessandro Bortotto, Mattia Dignani, Fabio Mattiazzi and Giuliano Degli Agli (in Fig.3.1) spent two weeks at the Novespace headquarters in Bordeaux, from October 16th to 29th , to take part to the 79th ESA Flight Campaign. In the first week the team had to assembly and test the experiment and pass the security check for Chaser, Target and Release System made by Novespace and ESA. In the second week, precisely in October 25th, 26thand27th, there were the three days of parabolic flights with the Novespace AirBus 310 in Fig.3.2. The debrief meeting after each flight was scheduled, where the team had to explain how the experiment behaved in micro gravity condition and the difficulties encountered during the flight. During the experiment there were only two operators, Operator 1 and Operator 2 for simplicity, having different tasks to repeat for every parabola.

3.1 Before the flight

The team organized a shipment from Padova to Bordeaux of the experiment, precisely to the Novespace headquarters. During the first week, the team had to ensure that the components of the experiment did not show damage after the shipment, moreover they had to test if Target, Chaser and Release System worked properly. Before the assembly of the experiment on the airplane, Novespace technicians, who take care about the safety of the airplane, wanted to control and check if the safety requirements of E/E and propulsion system were met to avoid

Figure 3.1: From the left to the right: Alessandro Bortotto, Mattia Dignani, Fabio Mattiazzi, Giuliano Degli Agli

Figure 3.2: Novespace AirBus 310

any hazardous or damage on the airplane. In particular, for the E/E system, the safety checks were focused on:

- the safety elements like the fuses, switches and display, were present in the system. Above all, they focused on the power supplies of the mock-ups and the Release System. For the Release System it was used the AC current provided by the airplane, so switching converters were used to supply the electromagnets and the sliders;

- the wiring, above all the connection between each electronic component;
- ground test for the Release System to avoid the risk of electric shock to a person in contact with it, if a fault occurs. The Release System had to be grounded and it was important to verify if the grounding value is under 5 ohm. Impedance shall be measured, through the use of a multimeter between any point of the experiment that is supposed to be grounded.

After the security check was completed, the experiment was assembled on the airplane. First the Release System and the baseplate for the computer laptops were fixed to the ground of the airplane, then the team completed the cabin layout with the wiring connections and fixing the 5 side net. The final result is in Fig.3.3.

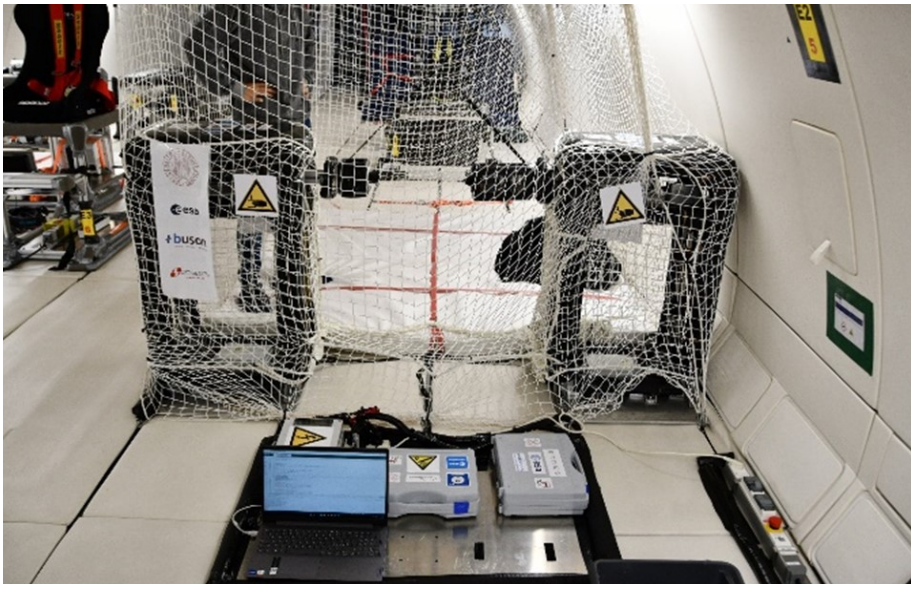


Figure 3.3: Final cabin layout

3.2 Flight activity

In the second week, in particular in the days before of the parabolic flights, ESA and Novespace explained deeply the schedule of one flight. The schedule of one flight counts in total 31 parabolas (30 parabolas dedicated to tests plus 1 parabola dedicated to getting used to the weightlessness condition). Every 5 parabolas there is a break of 5 min, moreover after the 15th parabola a break of 8 min is scheduled. As mentioned in the first chapter, each parabola is divided into four main phases:

1. **Standard-gravity phase**: initially the plane is flying straight, therefore the gravity level perceived is 1g. During this phase all the preparations for the experiment take place. The duration of this phase can vary depending on a series of factors.

2. **First Hyper-gravity phase**: the plane starts the ascendant phase, reaching an angle of 45°. The perceived g-level is around 1.8. In this phase, the experimenters are anchored to the floor thanks to seatbelts. This phase lasts around 20s.

3. **Low-gravity phase**: when the plane reaches the top of the parabola, the pilot lowers the engine power and the plane starts free-falling. Inside the plane, the perceived g-level drops under 0.01g for around 22s. During this phase, the experiment takes place.

4. **Second Hyper-gravity phase**: finally, the plane starts the descendant phase, reaching an angle of 45° and return to the standard-gravity phase, where the gravity is again 1g. This phase is analogous to the previous hyper-gravity one.

At the end of each flight, a meeting was scheduled to explain and discuss about the experiment.

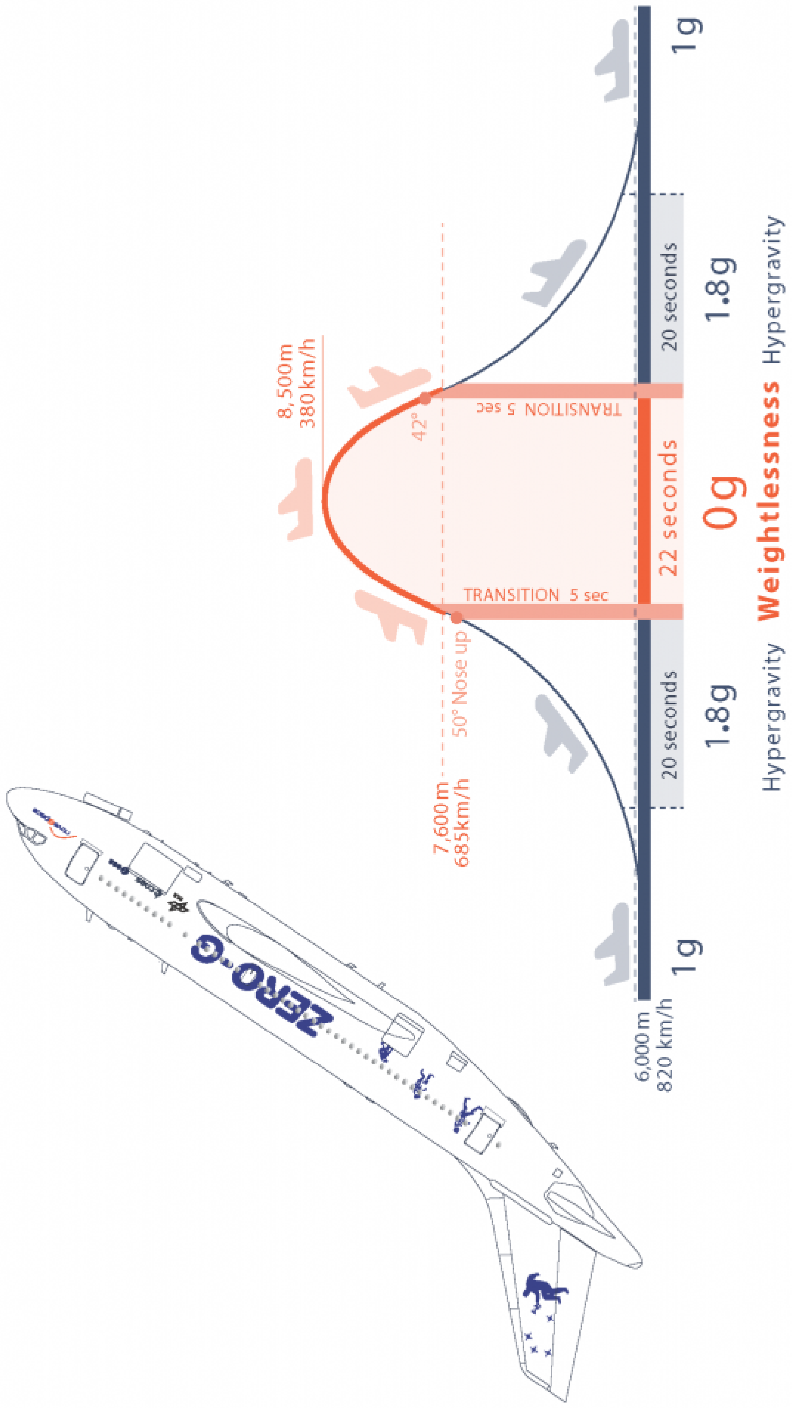


Figure 3.4: Parabolic Flight Scheme

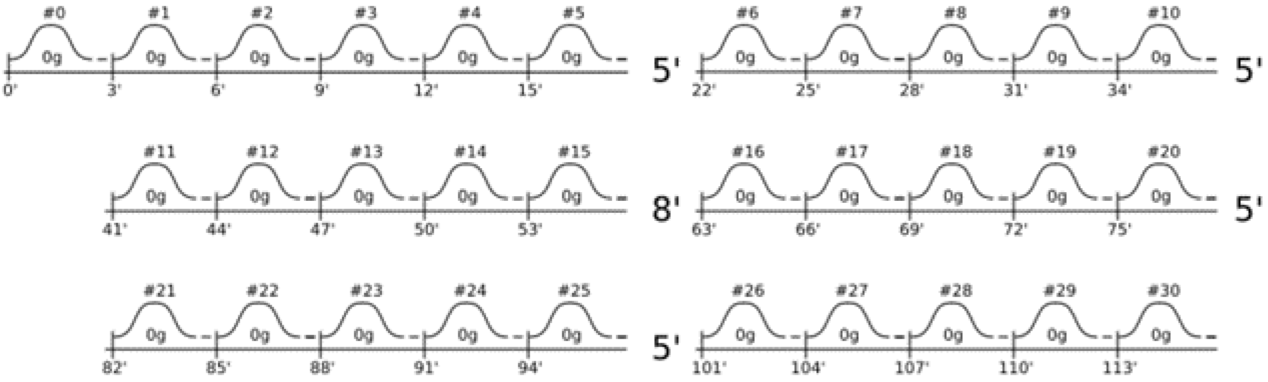


Figure 3.5: Parabolic flight schedule for one parabola

Moreover, the team had to follow the activities to do during the flight:

- During the standard gravity phase, the Operator 1 must insert the CO2 cartridge, turn on and check the voltage of the batteries of both mock-ups and place both on the electromagnets of the Release System. In the meanwhile, the Operator 2 turns on the electromagnets from the laptops to lock the two mock-ups. Then, both operators must sit in front of the baseplate, bounded by belts to avoid the free floating.

- During the low gravity phases, the initialization of the experiment is autonomous: since one parabola lasts 22 seconds and since the gravity is at a minimum in the middle, the experiment starts 8 seconds after the start of the Low-gravity phase, considering that the duration of the experiment is of 8 seconds. In the meanwhile, each operator shall sit near the laptop, both anchored in place with straps.

- During the hyper gravity phase the operators stay still on their positions, in front of the laptops.

- During the steady phase between two parabolas (standard gravity level – 1g) Operator 1 shall relocate the mock-ups on the electromagnetic constraints and eventually change the cartridges if it is empty. Meanwhile, Operator 2 activates the electromagnets to lock the two mock-ups and save the data of the telemetry received from the mock-ups. Then, after the preparation for the experiment has been completed, each operator shall sit near the laptop waiting for the start of the parabola. This task must be repeated before each parabola, when the airplane is in the standard-gravity phase.

- During the 5 min breaks, Operator 1 shall change the cartridge and the batteries of the Chaser as well as relocate both mock-ups. Moreover, during this short break it is highly recommended to check the correct functioning of the cameras since sometimes unwanted reboots or shutdowns could occur.

- During the 8 min breaks, Operator 1 changes the batteries of both mock-ups and cameras, cartridge and finally relocate the mock-ups.
- Finally at the end of all parabolas, the experiment must be shut down. The operators recover the mock-up and turn off the Chaser, Target and Release System.

3.3 Report of the flights

In this section there will be a briefly report of the flights. It is important to underline that some of the parabolas were not perfect, reproducing a microgravity environment with disturbances, explained in the chapter. Unfortunately these parabolas ruined a lot of parabolas and the experiment did not go as expected. But the rest of the parabolas were pretty good, others even better, so the team got the data required to do a good post processing phase.

3.3.1 First flight

In the first flight, the Operator 1 was Alessandro Bortotto and the Operator 2 was Fabio Mattiazzi. The first ten parabola was dedicated to getting used to the 0g and to the routine. Initially it was very difficult to understand how to move willingly and without losing control of ourselves. Regarding the testing, the parabola in which the experiment took place correctly was the first 15 (including the first set of parabolas dedicated to getting used to it). During the first parabolas, the experiment worked well. Above all, the team checked visually that the the opening and closing of the electrovalves, allowing the Chaser to move in the space depending on the trajectory calculated by the Raspberry Pi4. Around the 16th parabola, the Chaser, during the 2g phase, fell and hit with its frontal face the metal baseplate of the Release Structure of the Target by passing through a hole in the net. This impact damaged the ToFs and disconnected the power wire of 4 electrovalves. The damage was fortunately relatively light compared to the gravity of the impact. Moreover, since the Chaser did not show any visible damage, the team was unaware of the effect of the fall and decided to not change the mock-up with the spare one during the flight. Therefore, for the rest of the flight the Raspberry Pi4 kept sending commands to the Arduino NANO to control the solenoid valves correctly, but The Target had a gyroscopic rigidity lack which didn't allow it to stay still. The consequence is that each docking failed because when the Chaser touched the Target, it moved away from the Chaser. Another problem the team had to face was the release time, or else the time where the Release System started the launch. As mentioned before, the experiment starts after 8 seconds of the airplane reaches the peak of the parabola. Due to the difficulty of the operators to move during the low gravity phase, the Release System starts to work with a delay of exactly 8 seconds in order to have a good low gravity environment. So it was needed to understand at what exact time the Release System has to turn on.

⋆ **E/E systems**

The E/E system of the Chaser did not show problems until an unexpected impact on the metal baseplate. After that impact, as mentioned before, the Chaser did only pitch movements upward and downward and the result was a static position of the Chaser in front of the Target. After the flight, a deep check of all E/E system of the Chaser showed that one power line of the boost converter which supplies four solenoid valves disconnects due to the impact. For this reason, the Raspberry Pi4 entered in a 'loop' where the commands send to the Arduino NANO for the control of the solenoid valves was right, but four of them were disconnected, so there was not a right combination between the solenoid valve, and the only movements the Chaser did was the pitch, upward and downward. This disconnection was repaired and the wire has been welded better on the boost converter. The rest of the E/E system did not show other problems. The E/E system of the Target and of the Release System worked as expected and did not show any problem.

3.3.2 Second flight

In the second flight, the Operator 1 was Alessandro Bortotto and the Operator 2 was Giuliano Degli Agli. In second flight, unfortunately, the majority of parabolas were lost due to an unexpected disconnection between the Raspberry Pi4 and the laptop through the ssh connection. This type of disconnection was never experienced in any test in the laboratory and came unexpectedly. The team was able to face and solve this problem around parabola 18th. To avoid this problem, after the flight a backup connection was setup so that if the Chaser would disconnect again, it would be already prepared another connection to use. In the meanwhile, tests on the timing of release have been carried out, increasing the know out on this particular problem. The manoeuvres completed were interesting but with a better timing of release than the first flight and, consequently, a larger time dedicated to the manoeuvres. The 27th parabola is particularly interesting since the docking manoeuvre has been the most precise of all of them.

⋆ E/E systems

During the second flight, the E/E system showed no problems and their behavior was as good as expected.

3.3.3 Third flight

In the third flight, the Operator 1 was Alessandro Bortotto and the Operator 2 was Mattia Dignani. The third flight was the most positive one in terms of manoeuvres tested. The manoeuvres completed were interesting and similar to the second flight thanks also to the knowledge acquire in the first two flights. The 17th parabola is the most interesting of the entire flight since the docking manoeuvre has been precise.

⋆ E/E systems

Even in this flight the E/E systems did not show problems, but during a battery pack change there were a damage on the E/E system power cable and the Chaser turned off. So the operators lost the five last parabolas. The third flight was the most positive of the three flights and the three E/E systems did not show problems. Before the 24th parabola, during the battery pack change of the Chaser, unfortunately the connector of the battery pack disconnected to the E/E system of the Chaser. It was an unexpected problem and not reparable at that moment so, after a little discussion between the operators, they decided to end the experiment and enjoy the last parabolas.

3.3.4 Analysis of one parabola

This subsection has the focus on the study of a successful parabola. There will be a deep analysis of the 27^{th} parabola of the 2^{nd} day (referred to as #2/27). Snapshots of the video recording of this parabola are shown in figure 3.6.

Figure 3.6: Parabola #2/27 - Snapshots from the video recordings

The graphs reported in figure 3.7 and 3.8 show the relative trajectory followed by the Chaser and the relative velocity with the respect to the Target during this parabola. The graphs are coherent with the one presented in chapter 2.5 in terms of layout (dotted lines, colours, etc.). The data shown the behavior of the mock-ups up to the impact against the Release Structure and the consequent complete separation of the mock-ups.

From the analysis of the graphs the following considerations can be made:

- The **duration of the manoeuvre** has been around $4s$. To speed up the manoeuvre, these tests have been carried out with a pushing release (in particular Mod 4) in order to induce a greater velocity to the Chaser. This choice is due to the experience acquired during Flight 1 in which the static releases have shown to be inefficient in assure that the mock-ups would not hit the floor, the ceiling or any other surface before even reaching the threshold.

- Regarding the **initial attitude alignment**, only the pitch is not near zero (around $-5°$), while the roll and yaw have a lower misalignment ($< 5°$). This initial discrepancy in pitch could have been due to the light bending due to the placement of the Chaser on the magnetic constraints.
- The increase in the **pitch misalignment** up to around 12.5° could be due to two different factors: a small downward disturbance during the release, or the initial misalignment that has been enhanced by the thrust along x-axis. However, it can be seen that when the mock-up reaches the tolerance limit (12°), it immediately corrects it.
- Differently, the **yaw trend** is near zero during the navigation, while increases during the approaching phase. Therefore, it required fewer corrections with the respect to the pitch.
- Furthermore, during the manoeuvre important influences on the **position along the y and z-axis** are registered. The initial misalignment is probably due to the same reason that caused the pitch one. Similarly to that case, it can be seen that when it reaches the limit ($20mm$) it corrects its trajectory.
- However, the **misalignment in different axis** did not happen at the same time, therefore the Chaser was able to correct them individually. The only two misalignment that happened at the same time are on the pitch and z-axis: however fortunately the combined effect mitigated both of them assuring that the Target remained visible throughout the manoeuvre.
- Regarding the **velocities** during the manoeuvre, registering higher ones with the respect to the tests in the laboratory was expected. Consequently, also stronger thrusts were expected.
- As a consequence of all the previous analysis, the Chaser enters the approaching phase towards the Target with parallel face-to-face conditions (roll, pitch and yaw nearly null) but without a precise alignment along the y and z-axis (both lower than $10mm$). In this case, the conical design of the **docking interface** should have helped to correct it. In fact, the misalignment can be recovered by sliding between the two contact surfaces and

then establishing the connection thanks to the attraction between the two magnetic interfaces. Nevertheless, destabilising contact forces between the interfaces have been registered, causing in most cases the failure of the manoeuvre. The reason behind this unexpected behaviour during the docking final moments is due to the insufficient gyroscopic rigidity of the Target. At such velocities (around $3cm/s$), it has not been able to stabilize itself while impacted. Therefore it can be stated that the Target performed in an acceptable manner throughout the entire experiment, generally avoiding high misalignment but the Target suffered a lot the collisions with the Chaser.

- After the impact all the momentum is shared between the two mock-ups resulting in a backwards movement.

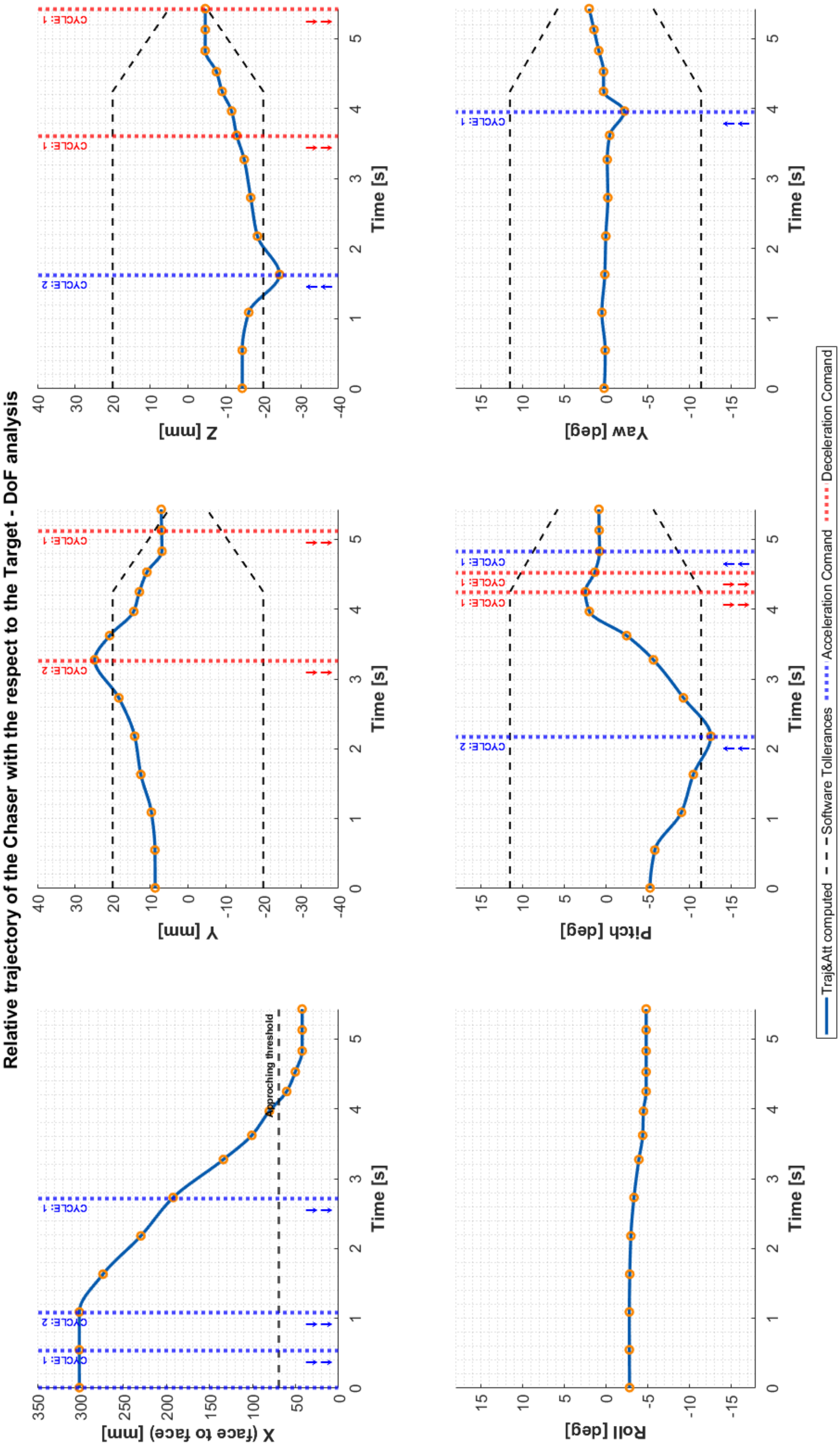


Figure 3.7: Parabola #2/27 - Relative trajectory of the Chaser with the respect to the Target

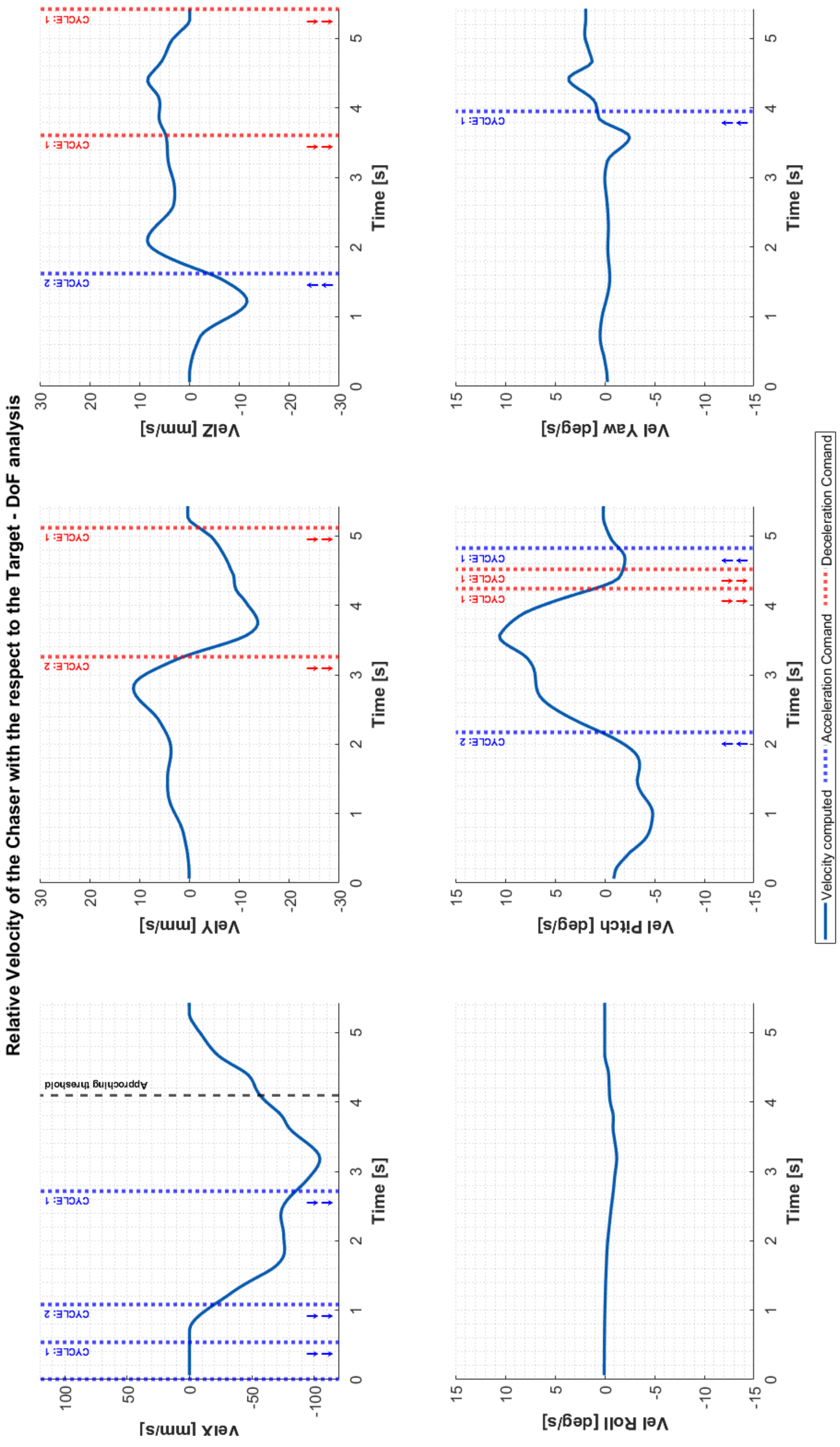


Figure 3.8: Parabola #2/27 - Relative velocity of the Chaser with the respect to the Target

In conclusion, in the Parabola #2/27 the docking manoeuvre was accomplished with an acceptable final alignment between the mock-ups.
The duration of the manoeuvre was not the one expected but by implementing pushing releases it has been possible to perform it up until docking. The pitch angle has been recovered from the initial misalignment and the misalignment encountered in the other axes have been recovered. Moreover, subsequently to the impact between the docking ports, a temporary state of good stability has been registered and the contact between the surfaces of the docking interfaces was soft enough to guarantee at least partially the sliding process. However, the collision pushed back the Target causing a crash with its Release Structure. In summary, the software performed as intended and with acceptable errors also considering its simplicity.

Chapter 4

Conclusions

Experimental Rendezvous in Microgravity Environment Study, briefly ERMES, is a project of the University of Padua carried out by Master Degree students and it has the aim to develop and test two Cubesat mock-up an autonomous docking experiment made by two free-floating CubeSat mock-ups in a reduced gravity environment. This thesis has the aim to show and explain the electric and electronic systems of the two Cubesat mock-ups, the Chaser and the Target, and their Release System. First, the thesis shows the description of the experimental setup of the experiment: for the Chaser, Target and Release System, a description of what they are and their behavior during the experiment is provided with a list of all the electronic components used to assembly the E/E systems. In particular, there is a description of the design for the PCBs and for the power supplies used with the power budget and the wiring. A test carried out in the laboratory is also provided to prove the behavior of the Chaser and the Target during the experiment. This test was important to understand and to improve all the subsystems involved for each mock-up. There is a description of the $79th$ Parabolic Flight Campaign where the team had the opportunity to test the ERMES experiment in a microgravity environment. During the first week, the team had to test the functionality of the Chaser, the Target and the Release System with the Novespace technicians. Moreover, they did also a safety checks of the E/E systems to avoid any risk of fire or damage during the experiment. The second week is composed by the three flights through the Novespace Airbus 310. One flight is composed by 31 parabolas, where the microgravity environment starts when the airplane reaches the peak of the parabola. At that moment, the experiment starts. At the end, there is the analysis of one successful parabola, where it shows the behavior of the Chaser and the Target.

In conclusion, it can be stated that during the 79^{th} ESA Parabolic Flight Campaign the experiment worked as expected, but at the same time the team had to face some unexpected problems that partially impacted its functionality and effectiveness. Therefore, the results of the flight campaign are positive. Going deeply on the analysis of the results, the experiment must be deconstructed up to its core objectives to identify exactly the strengths of this design and the possible errors. Finally, facing a precise analysis of the experiment as a whole, it is interesting to evaluate improvements for future iterations.

In order to evaluate the grade of success of ERMES, the objectives of ERMES have been deconstructed as follows: **Development [D]**, **Safety [S]** and **Campaign [C]**. Then for each task, a grade of successful (called $VAL\%$) is given and compared to the weight (called $W\%$) with respect to the entirety of the experiment (see table 4.1).

- **Development [D]**
  It concerns all the tasks of Design, Manufacturing, Assembly and Testing of the experiment carried out prior to the campaign. The total weight of the contribution of this category on the success rate of the experiment is 25%.

  1. Design, Manufacturing and Assembly of a cold gas propulsive system for the Chaser according to Novespace Guidelines;
  2. Design, Manufacturing and Assembly of a system of RWs for the Target according to Novespace Guidelines;
  3. Design and Testing a localization software implementing Apriltags;
  4. Design and Testing a simple Proximity Navigation Software;
  5. Design, Manufacturing and Assembly of a mechanical release system;
  6. Testing the entire experiment on Laboratory;

  Between all the above-mentioned objectives, half of the total weight of this category is given to objective #6 due to its importance. The other objectives share the same weight (see table 4.1).

- **Safety [S]**
  It concerns all the tasks relative to the risk and hazard management. The importance and gravity of such topics are the reason why this category is separated from the previous one, although it complements it. The total weight of the contribution of this category on the success rate of the experiment is 15%.

7. Prepare a complete and precise risk and hazard analysis;
8. Design and Implement solutions for safety management according to Novespace Guidelines;

The total value is split in half between the two.

- **Campaign [C]**
  It concerns all the tasks that characterized the preparation for the campaign and the flights themselves. The total weight of the contribution of this category on the success rate of the experiment is the highest, the 60%, because it has the most important objectives such as the one relative to the autonomous docking manoeuvre.

  9. on-board the experiment on the Airbus310;
  10. Chaser - Follow the trajectory computed in a low-gravity environment;
  11. Target - Perform cooperative attitude control in a low-gravity environment;
  12. Manoeuvre - Dock accomplished;
  13. Test and compare the two docking interfaces;

  The one with the greatest significance is the objective regarding the Docking itself, whose weight is set to 25%. This objective regards the actual connection between the mock-ups, therefore the “successful” manoeuvres described in the previous chapter are not considered an accomplished docking manoeuvres.

As reported in table 4.1, the ERMES experiment achieved a total of 72.5% of all the objectives. The only two objectives that have not been fully achieved were the one regarding the accomplished docking manoeuvre (#12), and the one regarding the testing of the two interfaces (#13).
Regarding the docking manoeuvre, the task has been set partially achieved because the magnetic connection between the dock interfaces of Chaser and Target has not been established (so the Chaser did not dock the Target completely), but during the post-processing analysis of the parabola, the trajectory of the Chaser was precise enough to show that the two docking interfaces have come into contact, but they did not dock completely due to the gyroscopic rigidity of the Target. Moreover, since only one docking interface has been partially tested

N	CAT	CRYTERIA	W%	VAL%
1	D	D.M.A. of a cold gas propulsive system	3	3
2	D	D.M.A. of of a system of RWs	3	3
3	D	D.T. a localization software	3	3
4	D	D.T. a simple Proximity Navigation Software	3	3
5	D	D.M.A. of a mechanical release system	3	3
6	D	T. the experiment on laboratory	10	10
7	S	Prepare a risk and hazard analysis	10	10
8	S	D.I solutions for safety management	5	5
9	C	Board the experiment on the Airbus310	5	5
10	C	C - Follow the trajectory computed	10	10
11	C	T - Perform cooperative attitude control	10	10
12	C	Dock accomplished	25	5
13	C	Test and compare the two docking interfaces	10	2.5
TOT			**100**	**72.5**

Table 4.1: ERMES Objectives

(probe-drogue docking interface), for the task #13 the achieved value is 2.5% out of the total weight of 10%. This value is still under half of the weight because, since the docking did not happen as planned, the probe-drogue docking interface can not be considered fully tested either.

Nevertheless, all the subsystems involved in both Target and Chaser worked well together and performed according to the test results in the laboratory. Therefore, ERMES, as a technological demonstrator, has been able to confirm the validity of the integration of many different technologies and subsystems in view of an autonomous docking manoeuvre. Above all, the E/E systems of Chaser showed problem during the first and third flight: in the first, there were a disconnection between the boost converter and one power line of four solenoid valves; in the third, there were a disconnection between the connector of the battery pack and the E/E system, making the Chaser not usable. But generally the E/E systems worked very well and as expected.

On the other side, considering the educational aspects, the ERMES project has been an amazing opportunity for all its member to enhance their academic career. In fact, during the journey of ERMES, the team members not only improved their knowledge of space-related topics but also their indispensable troubleshooting skills. In general, they experienced an all-around immersion in a work-like environment. In addition, the experience included presentations at important congresses and symposiums thanks to the different article productions. Finally, the project helped all the members to improve their interpersonal and management skills thanks to the help of the mentorship of the endorsing professors, researchers of the University and ESA supervisors with whom the team continuously interact.

In conclusion, the ERMES experiment has ensured the fulfilment of a lot of its objectives, meanwhile showing plenty of room for improvement. Unfortunately, the team did not achieve some of the desired results, but, given the complexity and ambitiousness of the experiment, the ERMES experiment can be considered a partial success.
Furthermore, since ERMES has been created as a successor of previous experiments of the *Università Degli Studi di Padova*, naturally I hope that future works by other student teams will rise, inspired by the ERMES project.

References

[1] URL: `https://it.wikipedia.org/wiki/American_wire_gauge`.

[2] URL: `https://it.wikipedia.org/wiki/Ruota_di_reazione`.

[3] *Adafruit Motor Shield V2*. URL: `https://cdn-learn.adafruit.com/downloads/pdf/adafruit-motor-shield-v2-for-arduino.pdf`.

[4] *Adafruit TCA9548A*. URL: `https://cdn-learn.adafruit.com/downloads/pdf/adafruit-tca9548a-1-to-8-i2c-multiplexer-breakout.pdf`.

[5] Francesco Branz et al. "Miniature docking mechanism for CubeSats". In: *Acta Astronautica* 176 (June 2020), pp. 510–519. URL: `https://www.sciencedirect.com/science/article/pii/S0094576520304082`.

[6] *Break-Out-Board AN1953*. URL: `https://www.microchip.com/downloads/en/appnotes/00001953a.pdf`.

[7] *Compact Proportional Solenoid Valve Series PVQ*. URL: `https://docs.rs-online.com/02fd/A700000006738966.pdf`.

[8] Robo Cylinder. *ERC Actuator with Integrated Controller, operation manual*. URL: `http://www.intelligentactuator.com/pdf/manuals/ERC_manual.pdf`.

[9] *DC-DC converter MDS series*. URL: `https://www.mouser.com/datasheet/2/260/MDS20_spec-1772011.pdf`.

[10] *Digilent Pmod™ Interface Specification*. URL: `https://docs.rs-online.com/16ce/0900766b815e6481.pdf`.

[11] ESA. *ESA Education Fly Your Thesis! (FYT) Programme*. URL: `https://www.esa.int/Education/Fly_Your_Thesis/About_Fly_Your_Thesis` (visited on 04/01/2023).

[12] *Faulhaber flat DC-micromotors series 2607*. URL: `https://www.faulhaber.com/fileadmin/Import/Media/EN_2607_SR_DFF.pdf`.

[13] *MOSFET IRL40B215*. URL: `https://docs.rs-online.com/2bcd/0900766b814348a0.pdf`.

[14] Novespace. *Novespace*. URL: https://www.airzerog.com (visited on 04/01/2023).

[15] *NOVESPACE Experiment Design Guidelines in Parabolic Flight*. 2021.

[16] Raspberri Pi. *Raspberry Pi4 Model B*. 2019. URL: https://datasheets.raspberrypi.com/rpi4/raspberry-pi-4-datasheet.pdf.

[17] *Pmod NAV Reference Manual*. URL: https://docs.rs-online.com/8dd8/0900766b815970f5.pdf.

[18] *Rechargeable AA NiMh battery, 1.2 V, 2.5Ah*. URL: https://it.rs-online.com/web/p/batterie-aa-ricaricabili/7033515?cm_mmc=IT-PLA-DS3A-_-google-_-CSS_IT_IT_PMAX_Catch+All-_--_-7033515&matchtype=&gclid=EAIaIQobChMI6JmOl5DfgQMVEAqiAx3mgA5MEAQYAiABEgIMfvD_BwE&gclsrc=aw.ds.

[19] *RS PRO 6v NiMh rechargeable battery pack*. URL: https://docs.rs-online.com/bdbf/A700000007955124.pdf.

[20] *Slider ERC2-SA6C*. URL: http://www.intelligentactuator.com/partsearch/robocylinder/pg055_ERC2-SA6C.pdf.

[21] *Technology CubeSats*. URL: https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Technology_CubeSats.

[22] *ToF VL6180X*. URL: https://www.st.com/resource/en/datasheet/vl6180x.pdf.

Ringraziamenti

Giunto al termine del mio percorso universitario, si concludono sette faticosi anni di studio, ma belli ed intensi grazie ai quali sono cresciuto e diventato la persona che sono oggi. È stata proprio la frase "Prova a lasciare un segno" che mi ha spinto ad intraprendere il percorso della Magistrale. Compresi che per sentirmi un giorno pienamente soddisfatto avrei dovuto fissare obiettivi che mi avrebbero fatto crescere sia personalmente che professionalmente. Ad oggi quindi posso dire di essere felice che sia finita nel modo in cui io stesso desideravo e fiero per tutto ciò che sono riuscito a fare.

Il mio "viaggio" parte con il progetto ERASMUS. I sei mesi vissuti in Norvegia hanno accresciuto in me la passione per quello che stavo studiando e mi hanno permesso di prender parte e di lavorare al grande progetto di ERMES, oggetto della mia tesi di Laurea.
A tal proposito è doveroso ringraziare il Professor Francesco Branz, per avermi permesso di lavorare nel suo laboratorio durante il percorso di ricerca per il progetto ERMES, per la sua collaborazione e aiuto datomi non solo nello sviluppo di questa tesi, ma anche nella mia crescita professionale.

Ringrazio il team ERMES per avermi scelto come loro membro e per aver condiviso insieme un'esperienza unica ed indimenticabile. Non avrei mai immaginato di poter lavorare con un volo parabolico. Una menzione speciale va ad Alessandro Bortotto, con il quale ho condiviso successi e fallimenti, risate e difficoltà, instaurando un rapporto di professionalità e rispetto reciproco.

Un Grazie va alla mia famiglia allargata perché non sarei qui senza di voi. Grazie per aver permesso tutto questo, per avermi sempre sostenuto in ogni mia scelta e per la fiducia che mi avete sempre dato.
Ringrazio i miei fratelli Luca, Riccardo, Pietro e Tommaso per essere cresciuti insieme.

Ringrazio i miei coinquilini e compagni di avventure Giulio, Alberto ed Edoardo. Anche se solo per un anno, vi ringrazio per aver vissuto insieme a me tutti quei momenti che porterò sempre dentro, tra film, giochi, sessioni di esami e post-esami, insieme a loro ringrazio anche i miei amici "Padovani" Tommaso, Anna, Vera e i miei compagni di corso Giulio e Giorgia.

Ringrazio tutti i miei amici, quelli che mi conoscono da tempo e quelli che ho scoperto in questi anni. Grazie per aver avuto sempre per me parole di sostegno, di supporto e soprattutto di consiglio che porterò dentro. Tutti i bei momenti vissuti insieme sono stati per me fonte di crescita. Sono certo che i veri legami continueranno a camminare e crescere insieme a me nel percorso di vita.

Infine, ma non meno importante, un ringraziamento speciale va a Sara, la mia dolce metà, per aver vissuto insieme a me questi due anni. Grazie per essere rimasta al mio fianco, sempre ed incondizionatamente, anche quando le difficoltà erano immense e tutto ci sembrava impossibile. Al tuo perenne ed unico sostegno, alla tua costante presenza, a tutto quello che riesci a darmi ogni giorno, a tutto quello che ho imparato da te. Se sono qui oggi è anche grazie a te.