École Polytechnique Fédérale de Lausanne

Project PrOXISS

Proximity Operation eXperiment on the International Space Station

Feasibility Study for Uncooperative Object Capture in Microgravity

In collaboration with EPFL eSpace Center,
ClearSpace, CSEM, EPFL CVLab, Galactic Studios, Klepsydra Technologies

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Executive summary

This report is the result of a joint semester project by two EPFL master's students. It presents a comprehensive feasibility study for the PrOXISS mission (Proximity eXperiments on the International Space Station), aimed at advancing technologies critical for On-Orbit Servicing and Active Debris Removal through microgravity experiments inside the ISS. The PrOXISS project was initiated in response to the Swiss Space Office's call for experiments supporting ESA astronaut Marco Sieber's upcoming mission to the ISS (2027-2029).

After clearly defining the mission and its objectives, stakeholders' expectations and constraints are described. This enables to draft a first version of the high-level requirements and of the ConOps and propose a system architecture, especially the propulsion. This document also outlines areas of improvement in the original SSO submission and proposes alternative approaches, such as the use of Astrobee or the use of ArUco markers. Additional recommendations were presented and enable the reduction of mass budget by 2 and the crewtime budget by more than 3.

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Introduction

Context

This paper is the result of a joint student project between two master's engineering students from EPFL, who have collaborated and worked together on a feasibility study for the mission called *PrOXISS* (Proximity eXperiments on the International Space Station). This paper does not only reflect the results of the student's semester project, but is intended to be used as a reference for the stakeholders when moving forward with this project.

Marco Sieber, a recently qualified Swiss ESA astronaut, will have his first mission to the International Space Station (ISS), which is expected to take place between 2027 and 2029. The Swiss Space Office (SSO) issued a call for interest for scientific and technological experiments to be conducted during his mission. This Call was open to Swiss institutes and companies and the deadline was in January 2025. In answer to this call, the eSpace EPFL Space Center, ClearSpace, CSEM, EPFL CVLab, Galactic Studios and Klepsydra have gathered and submitted a three-pager for the PrOXISS mission.

To pave the way toward On-Orbit Servicing, PrOXISS aims to test techniques and strategies for capturing uncooperative targets in microgravity using a small robotic chaser spacecraft inside the ISS. The experiment will advance technologies essential for On-Orbit Servicing and Active Debris Removal (ADR), to ensure continued access to space for future generations, thus supporting sustainable space operations. It will also aim to maximize the experiment's impact on outreach and education.

Objectives of the semester project

While waiting for the feedback and acceptance of this proposal, this student project aims to define preliminary high-level requirements, draft a ConOps for technology demonstration in microgravity, and propose a propulsion system architecture. These preparatory activities are intended to ensure the project can progress efficiently once formal approval is granted.

The **questions** that are being tackled in this paper are the following:

- What are Stakeholder's expectations?
- What are the main constraints that will drive the design in early project phases?
- What are the high-level requirements, based on stakeholder expectations and other flow-down requirements?
- How would a ConOps look like for a technology demonstration / experiment on a parabolic flight and on the ISS?
- How could and should the propulsion system look like?

The main **deliverables** of this project are:

- Feasibility Report / Clear Recommendations and mitigation strategies
- Mission Definition
- State of the Art
- Stakeholder Map and Roles
- Constraints Analysis
- Function Tree
- Preliminary High-Level Requirements

- Concept of Operations (ConOps)
- Risk analysis
- Preliminary Timeline
- System Trade-offs
- System description
- Subsystems design, especially payloads and propulsion

Acknowledgment

We would like to express our sincere gratitude to everyone who contributed to the success of this project. First and foremost, we thank Emmanuelle David and Andrew Price from the EPFL Space Center for their guidance as our supervisors. Their experiences in space applications greatly enriched the quality of the work presented here.

We are also deeply appreciative of all the stakeholders for their time and help: Kees van der Pols and Jacques Viertl from ClearSpace, Antoine Ummel and Stéphane Humbert from CSEM, Andrew Price again from EPFL CVLab, and Chloé Carriere from Galactic Studios. This project would not have been possible without their contributions.

Special thanks are extended to Marcel Egli from HSLU (Hochschule Luzern), Adrien Saada from CNES (Centre National d'Etudes Spatiales), and Volker Koehne from ESA for their advice on ISS experiments design and operations. We also thank Nicolas Durand, former EPFL student who worked with his team on the "Projet Colibri", a similar project on a small controlled robot in microgravity that inspired our work.

Lastly, we wish to thank the EPFL Space Center for their academic support, which was instrumental in bringing this work to fruition.

Definitions and abbreviations

Acronym	Definition
ADR	Active Debris Removal
ADCS	Attitude Determination and Control System
AI	Artifical Intelligence
AOCS	Attitude and Orbit Control System
CADMOS	Centre d'aide au développement des activités en micro-pesanteur et des opérations spatiales
ConOps	Concept of Operations
COTS	Components Off the Shelf
CSA	Canadian Space Agency
CSEM	Swiss Centre for Electronics and Microtechnology
DARPA	Defense Advanced Research Projects Agency
DoF	Degrees of Freedom
EDF	Electric Ducted Fan
EPFL	Swiss Federal Institute of Technology Lausanne
EPS	Electrical Power System
ESA	European Space Ageny
FAP	Far approach point
GEO	Geostationary Orbit
GNC	Guidance Navigation and Control
GPS	Global Positioning System
GPU	Graphical Process Unit
IMU	Inertial Measurement Unit
IOS	In-orbit Servicing
IPP	Initial Proximity Point
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
LAN	Local Area Network
LEO	Low Earth Orbit
MAIT	Manufacturing, Assembly, Integration and Testing
MPCC	Multi-Purpose Computer and Communication
NASA	National Aeronautics and Space Administration
OBC	Onboard Computer
PF	Parabolic Flight
PrOXISS	Proximity Operation eXperiment on the International Space Station
REACCH	Responsive Engaging Arms for Captive Care and Handling
RF	Radio Frequency
rpm	Revolutions Per Minute
RPO(D)	Rendezvous and Proximity Operations (and Docking)
TRL	Technology Readiness Level
SCNAT	Swiss academy of sciences
SFTP	SSH File Transfer Protocol (or Secure File Transfer Protocol)
SLAM	Simultaneous Localisation and Mapping
SSH	Secure Shell Protocol
SSO	Swiss Space Office
SVN	Stakeholders Value Network
SXS	Space eXchange Switzerland
VR	Virtual Reality

1 Mission statement and description

1.1 Context

Space sustainability and the problem of space debris is a rising topic. Advancements in space robotics are needed to support missions involving satellite servicing and active debris removal. Important technologies such as object detection, relative navigation, and capture must be validated to ensure viability of these missions. The microgravity conditions of space present unique challenges for testing these systems, particularly in scenarios involving uncooperative or passive targets. Several swiss actors formed a consortium, composed among other by EPFL, CSEM and ClearSpace, to tackle these challenges. EPFL is a university of engineering that leads research on space sustainability, CSEM is a well-established research and development company and ClearSpace is at the forefront of ADR with a real mission in the coming years. They all decided to propose an experiment to test some of the technologies developed for an ADR mission.

1.2 Mission statement

To advance technologies for pose estimation and relative navigation using LiDAR, and to achieve successful capture of a passive uncooperative object, by conducting experiments in a microgravity environment, to support the development of technologies for space debris mitigation and on-orbit servicing, and raise public awareness.

The overall mission goal is therefore: Autonomous identification, approach and capture of an uncooperative client in microgravity, based on LiDAR information, computer vision & relative navigation algorithms, and with a capture system.

1.3 Objectives

O1 - Detect object The spacecraft shall detect an object using a LiDAR provided by CSEM.

O2 - Pose estimation The position of the client relative to the spacecraft, as well as its identification, shall be estimated using the LiDAR data by computer vision algorithms provided by EPFL CVLab.

O3 - Relative navigation The spacecraft shall navigate to the object with the GNC provided by ClearSpace.

O4 - Capture The spacecraft shall capture the uncooperative client in microgravity, using the capture system provided by ClearSpace.

O5 - Public engagement Communication around the mission will be handled by Galactic Studio to encourage public outreach and interest.

2 State of the art

This section will list missions and experiments on autonomous free-flying robotics and capture experiments on the International Space Station. The ISS hosts a variety of free-flying robots and technology demonstrations aimed at autonomous proximity operations, rendezvous, and capture in microgravity. Early work began with the **SPHERES** satellites (Synchronized Position Hold, Engage, Reorient Experimental Satellites), three bowling-ball-sized satellites flown on ISS since 2006. SPHERES flew in formation and tested autonomous control, navigation, mapping and docking algorithms (with NASA, DARPA and MIT) for over a decade. These experiments pioneered software and hardware for formation flight and relative navigation in weightlessness, laying the foundation for newer systems.

The next-generation free-flyer is **Astrobee**, a trio of cube-shaped robots (named Bumble, Honey, and Queen) deployed in 2019. Astrobee uses fans for propulsion and vision-based inertial navigation, and carries a perching "hand" to grasp station handrails or small items. It was specifically designed to relieve astronauts of routine tasks (inventory, experiment documentation, cargo movement) and to serve as a flexible research platform. Operated autonomously or by ground control, the Astrobees have logged over 1,200 hours in orbit supporting more than 150 investigations. They take over from SPHERES as the ISS's free-flying robotics testbed.

Figure 2.1: *The three Astrobee robots (©NASA)*

Astrobee has enabled numerous advanced demonstrations of ISS robotics. For example:

- Rendezvous & Proximity Operations: MIT and the German Space Agency (DLR) used two Astrobees in 2021–2022 to test algorithms for autonomous capture of a tumbling object. One "Chaser" Astrobee observed and modeled a spinning "Target" Astrobee with its cameras, then planned and executed a trajectory to rendezvous and dock with it. This TumbleDock/ROAM experiment validated complex SLAM (Simultaneous Localisation And Mapping), estimation and model-predictive control techniques for uncertain, spinning targets in microgravity.
- Vision-Based Guidance: In the SpaceX Crew-5 mission, Astrobees carried a Smartphone Vision Guidance Sensor experiment that used onboard cameras for navigation and alignment. This demo showed Astrobee using image cues for guidance, navigation and control inside Kibo. In general, Astrobees act as autonomous "eyes and ears" on station, performing inspections, monitoring experiments, and mapping the interior.
- Grasping & Capture: Astrobee has tested novel grippers for holding objects. One Stanford-led demo attached gecko-inspired adhesive pads to an Astrobee gripper. In April 2021, astronauts commanded this Astrobee to fly and "perch" on an ISS wall using the gecko pads. Similarly,

Germany's REGGAE project (DLR/TU Braunschweig) placed different gecko-type adhesive materials on Astrobees. ISS crew then had the Astrobees "grab" panels and sample surfaces (acrylic, MLI, aluminum) mimicking debris, confirming that these adhesives can latch onto tumbling, uncooperative objects in space.

- Multi-Arm Grappler (Responsive Engaging Arms for Captive Care and Handling, REACCH): In late 2024, Kall Morris Inc. flew its REACCH end-effector on Astrobee. This bio-inspired device has several flexible "tentacle" arms tipped with gecko-like pads. In ISS tests, Suni Williams outfitted an Astrobee with REACCH and had it autonomously detect, approach and grapple a free-floating passive and casi-immobile target cube (simulating debris). Ground controllers programmed Astrobee to find the target and reach out, successfully capturing it repeatedly. KMI reports that REACCH can secure and release objects of nearly any shape and surface, potentially enabling soft capture of diverse debris for future removal missions.
- Crew Assistance & Logistics: Beyond capture demos, Astrobees perform everyday support roles. They can autonomously carry scanners for inventory (RFID/REALM investigations) and even sample liquids or air. These tasks free astronauts to focus on science. In one mission log, Astrobees were described as "toaster-sized autonomous robots" assisting with station chores and giving ground teams additional monitoring capability.

These Astrobee experiments collectively advance autonomous proximity operations and capture. They demonstrate on-orbit the sensing, planning, and manipulator technologies (vision, SLAM, soft gripping) needed to rendezvous with and secure objects in microgravity.

CIMON is a free-flying artificial intelligence (AI) assistant developed by Airbus/IBM for the German Space Agency (DLR). Deployed in 2018, CIMON was designed to demonstrate autonomous navigation and human-robot interaction. In its first experiment, CIMON autonomously navigated the Columbus lab: it located and recognized ESA astronaut Alexander Gerst's face, took photos and video, and used ultrasonic sensors to position itself around the module. Powered by an onboard microphone and camera with voice-control via IBM's Watson AI in the ground cloud, CIMON could answer questions and guide Gerst through a student-designed experiment. For example, when Gerst said "Wake up, CIMON," it responded and then instructed him on a crystal-growth task. This demo showed that a free-flying robot can interact naturally with crew in microgravity. Although CIMON carries no arms and isn't meant to capture objects or host a payload, it represents an advanced test of autonomy and AI on the ISS. Engineers note that lessons from CIMON's design (autonomous flight, voice interface, networked control) will inform future robots for crew assistance on long-duration missions.

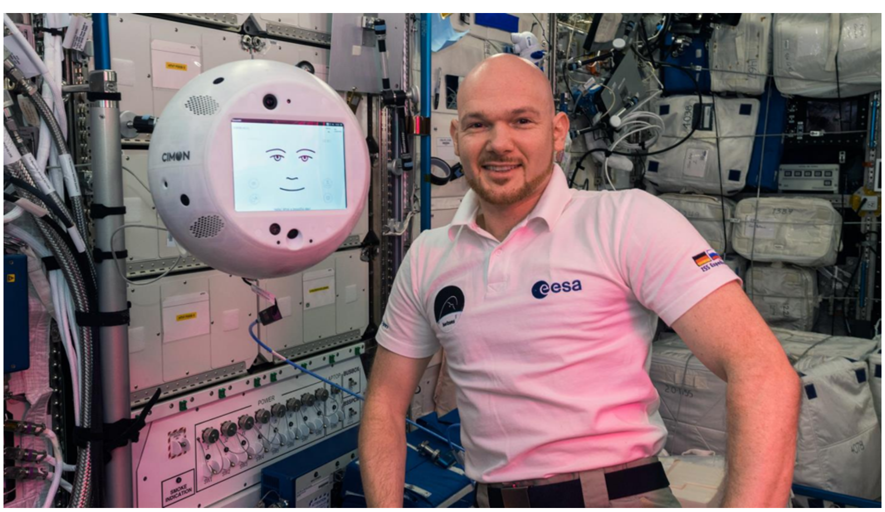


Figure 2.2: *ESA astronaut Matthias Maurer works alongside CIMON (©ESA/NASA)*

Int-Ball is JAXA's free-flying camera drone in Kibo. First flown in 2017, Int-Ball (and its successor Int-Ball2 in 2025) autonomously maneuvers around the Japanese module to take photos/videos of the crew. The sphere carries two wide-angle cameras and an inertial measurement unit (IMU) tied to a visual location system. This lets Int-Ball maintain orientation, navigate the module, and even dock itself for recharging. In operations, ground controllers remotely direct Int-Ball, but it can fly autonomously to capture the crew's work from any angle, significantly reducing the crew's photography tasks. JAXA's objectives include freeing the astronauts from ∼10% of their time spent on taking pictures, and enabling coordinated "one-view" monitoring by ground and onboard teams. Int-Ball has demonstrated that a small free-flying drone can reliably navigate the cluttered ISS interior using onboard sensors. Its success contributes to ISS robotic capabilities by proving the feasibility of an untethered camera drone in microgravity.

In summary, the ISS has served as a laboratory for cutting-edge free-flyer and capture research. The legacy SPHERES units proved formation control concepts, and Astrobee now enables a wide range of tests in relative navigation, rendezvous/docking, and robotic grasping. Key contributions include validating onboard guidance algorithms (MIT's TumbleDock), testing vision-based docking (SVGS), and demonstrating new grasping methods (gecko adhesives, multi-arm grippers). Projects like CIMON and Int-Ball explore autonomous navigation and crew assistance, broadening the scope of ISS robotics. Recent demos (e.g. KMI's REACCH on Astrobee) specifically target debris capture technologies, showing that soft, compliant manipulators can autonomously grapple free-floating objects in orbit. Collectively, these experiments advance the state of the art for autonomous proximity operations: they yield data and lessons on perception, planning, and manipulation in microgravity that will guide future satellite servicing and debris-removal missions.

3 Stakeholders and Constraints

3.1 List

The primary stakeholders are:

- eSpace - EPFL Space Center: Project Coordinator
- ClearSpace: Capture System (mechanical hardware and algorithms for approach trajectory algorithms, capture system and capture strategies)
- CSEM: LiDAR and vision-based sensing system
- EPFL CVLab: Computer vision algorithms
- Swiss Space Office (SSO): National authority overseeing Swiss space activities
- European Space Agency (ESA)

Secondary stakeholders include:

- Galactic Studios: Public Outreach and educational engagement
- Klepsydra Technologies: Artificial Intelligence
- National Aeronautics and Space Administration (NASA) of the United States of America

The Stakeholder Value Network (SVN) (figure 3.1) visually maps the relationships, responsibilities, and value exchanges among the main actors involved in the PrOXISS mission. It highlights eSpace at the center of coordination, supported by industrial partners such as ClearSpace, CSEM, and Klepsydra for subsystem development, and EPFL's CVLab for computer vision. Regulatory and strategic oversight is shown through the roles of ESA, SSO, and NASA, with links to astronaut Marco Sieber and operational entities such as CADMOS. Testing environments, including the ISS and parabolic flights via NoveSpace, are integrated through ESA coordination. Public engagement is represented by Galactic Studios, and communication channels are illustrated with color-coded arrows for technology, information, funding, and political influence. Additionally, while not explicitly detailed elsewhere, EPFL as an academic institution offers access to internal test facilities and student project infrastructure, which could be mobilized to support early prototyping, integration, or validation activities as needed.

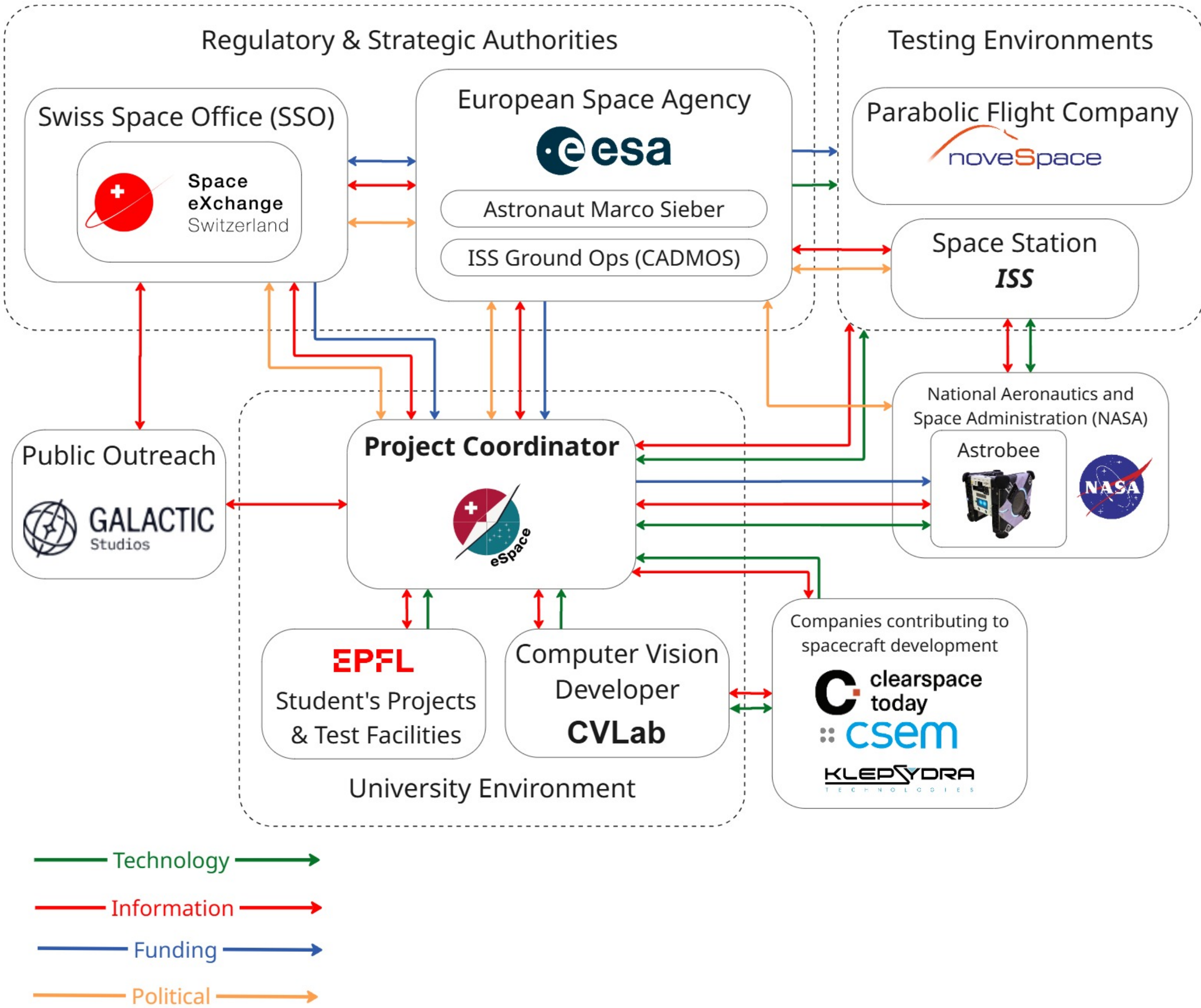


Figure 3.1: *Stakeholder Value Network*

Additional information: eSpace serves as the coordinator of the PrOXISS mission, overseeing the integration of all subsystems onto the chaser spacecraft and ensuring overall mission coherence. It acts as the primary liaison with the Swiss Space Office (SSO), ESA, and other relevant authorities, while also leading efforts to ensure compliance with ISS requirements and maintaining traceability from stakeholder goals to technical implementation.

ESA facilitates access to testing environments such as parabolic flights (through the NoveSpace campaign) and the International Space Station (ISS). ESA is also responsible for safety reviews, ISS payload integration, and astronaut coordination, in particular with Marco Sieber, Switzerland's second astronaut, who is expected to visit the ISS between 2027 and 2029. ESA will likely assign a Payload Engineer Expert to support the team through future safety and operational reviews.

The Swiss Space Office (SSO) is co-responsible for selecting and supporting Swiss space research initiatives. Together with ESA and the Swiss Academy of Sciences (SCNAT), SSO has issued a call for proposals for experiments that could fly during Marco Sieber's mission. This initiative is accompanied by Space eXchange Switzerland (SXS), which serves as a national platform to promote Swiss space activities and public engagement. Operated under the Swiss Academy of Sciences and funded by SSO, SXS focuses on public outreach, communication, and multimedia production to increase the visibility of Swiss contributions to space exploration, such as organizing events, publishing interviews, managing educational campaigns, and more.

The ISS itself enables microgravity demonstrations in a controlled, pressurized and crew-supported environment. This makes it suited to test the PrOXISS experiment's key objectives. NASA co-manages the ISS in collaboration with ESA, Roscosmos (Russian State Corporation for Space Activities), JAXA (Japan Aerospace Exploration Agency), and CSA (Canadian Space Agency). Coordination with NASA is expected indirectly through ESA and operational partners such as CADMOS (Centre pour l'Accroissement du Développement des Missions d'Orientation Spatiale), for ISS Ground Operations, based in Toulouse. In addition, NASA is the developer and operator of the Astrobee free-flyer platform, which is talked about later in this report.

Although multiple commercial providers exist for parabolic flights, NoveSpace (under ESA campaigns) is currently the most tangible partner for PrOXISS, offering a microgravity environment through brief periods of microgravity.

3.2 Expectations

It is extremely important to involve stakeholders in all phases of a project. It is also important to validate the stakeholder expectations in acceptable statements and obtaining the stakeholder commitments to the validated set of expectations. The stakeholder expectations have been collected and discussed through iterations of meetings and feedbacks. Table 3.1 shows the validated set of stakeholder excpectations.

The agreed-upon Mission Goal, as defined by all primary stakeholders is:
Autonomously identify, approach, and capture an uncooperative client in microgravity using LiDAR data (provided by CSEM), computer vision algorithms (developed by CVLab), and a mechanical capture system with supporting relative navigation strategies (developed by ClearSpace). Public outreach and communication surrounding the mission will be led by Galactic Studios.

Secondary objectives, such as a 360° live VR broadcast from the spacecraft onboard the ISS and remote control of the spacecraft from ground, are considered valuable enhancements but are not essential for mission success. Klepsydra Technologies is expected to contribute artificial intelligence software integration for onboard data processing, which is also a secondary objective. Their integration is planned for a later phase of the project.

Stakeholder/ Category	Expectations
ClearSpace - Validation of ConOps of Capture	Demonstrate the capture of various clients using real-time pose data, RelNav algorithms and strategy execution. The capture from closing to capture point (c.f. Conops section 6) is $<$ 60 seconds. Validating different approach trajectories, if it is possible within the given constraints. The capture system encloses the client in a volume it cannot escape from before the capture system touches the client. The attitude of the rigid stack is controlled.
ClearSpace - Client	The client can have different shapes and sizes, even including optional removable postrusions such as antennas. The client's mass is roughly 1/3 of the mass of the chaser. The client is sometimes immobile and sometimes slightly tumbling (max. 5°/s). The client's relative velocity is max. 5 cm/s.
ClearSpace - Capture System	The mass of the mechanical capture system is approx. 2kg. The peak power is below 50W. The capture system is 20 x 20 x 10 cm when stowed, and is a hemisphere defined by base of 70 cm x 70 cm x 10 cm to 30 cm x 10 cm x 10 cm at top.
CSEM - LiDAR	Demonstrate operation of their developed LiDAR for space applications.
CVLab - Computer Vision Algorithms	Develop and demonstrate computer vision algorithms, such as algorithms for pose estimation.
Galactic Studios	Speak and tell the story of the general project, about the spacecraft, about the people involved, about the importance of this project for IOS and ADR, etc. Tell stories about PrOXISS mission and the developped spacecraft. Inspiration of audience for youth & develop curiosity. Raise awareness of Swiss role in the space industry and space technologies. Set up a visual identity for the mission/spacecraft (e.g. comic book style character of spacecraft). Be part of bimonthly or regular meetings to stay updated about the mission development. Emphasize the space sustainability angle. Different kinds of outreaches, depending on the public: interviews with team members, newsletters about design iterations, workshops with youth and other audiences, etc.
ClearSpace, CVLAB, CSEM - Ground Truth Data	Data for post-processing the ground truth, and compare it with data measured from or with the chaser or client, in order to evaluate the performance of algorithms, sensors, etc.
ClearSpace, CVLAB, CSEM - Software maintenance and upgrade	Software can be upgraded remotely from ground to the ISS (flight software, algorithms, sensor configurations, etc.).

Table 3.1: *Validated Stakeholder Expectations*

Some initial expectations included the fly-around and motion synchronization trajectories of the chaser spacecraft, but are not possible because of the constraints of the testing environments (c.f. Constraints section 3.3). Moreover, the expectations of 360°-life-VR experience with remote control from Earth onboard the ISS has been put into a secondary objective, as it implies a lot of safety issues and complications. Furthermore, Galactic Studios said that there was no real added value of a VR live stream or that at least the trade-off between added value and cost of such an objective has to be carefully evaluated. A remote control of the spacecraft on the ISS from Earth was strongly discouraged. These mitigations and recommendations are summarised in 12.

Repartition of tasks and roles:
The onboard pipeline for autonomous client capture (figure 3.2) begins with data acquisition by CSEM's vision based system (LiDAR and other cameras, such as RGB cameras), which extracts a depth map (3D point cloud data) from the environment. This data, along with the camera intrinsics, is processed by CVLab's computer vision algorithms to identify the client, extract features, and estimate the client's relative pose. The resulting relative pose matrix is sent to ClearSpace's software, which computes the approach and capture strategy, based on the client's relative pose and environmental constraints. This command is executed by the propulsion system, followed by the capture of the client with the capture system, when the client is within reach. Moreover, the visual content that Galactic Studios needs for public outreach shall be provided by cameras on-board the ISS and/or on-board the payload, where CSEM is responsible for the cameras that provide the images.

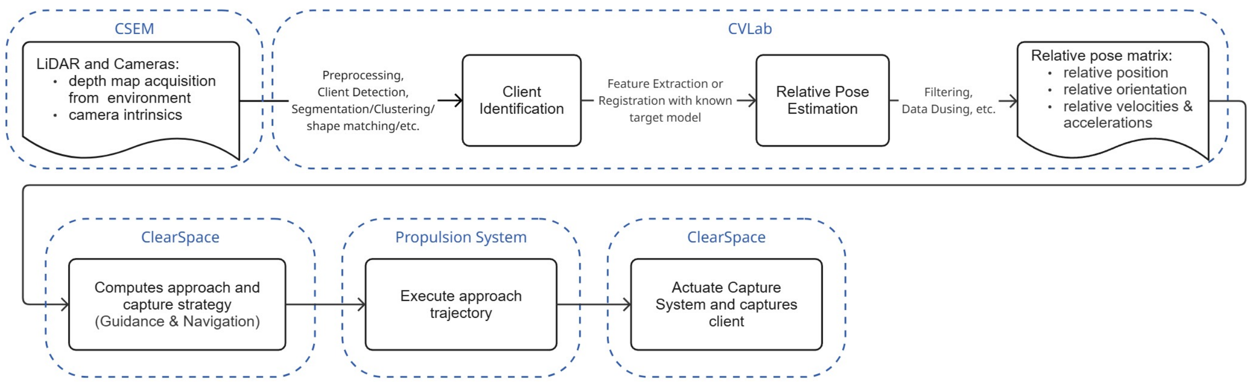


Figure 3.2: *Pipeline steps from client identification to capture*

3.3 Constraints

Now that the stakeholder expectations have been elicited and defined in acceptable statements, the constraints that may apply should also be identified. The execution of the PrOXISS mission is subject to a range of environmental, operational, and safety constraints defined for example by the test environments and the budgets.

These include microgravity platforms such as the Space Stations (e.g. ISS), parabolic flights, and ground-based testbeds like air-bearing platforms for friction-reduced mobility in order to test 2D microgravity dynamics. Each platform has specific constraints and the types of experiments it can support. Additional facilities such as cleanrooms, flat-sat test benches, or dark rooms can also be used for subsystem validation under representative conditions.

The following non-exhaustive list gives an idea of the purposes of testing environments relevant to this project. This does not serve as a verification plan.

Testing environment	Advantage / Purpose it can serve
Flat-sat test benches	Enables software testing, power distribution validation, and remote command execution. Suitable for testing software updates, health monitoring, telemetry flow, and data handling in a controlled, wired environment.
Clean room	Allows controlled mechanical testing and safe integration of the capture system. Used for actuation validation, physical tolerance checks, and capture–release cycling.
Dark room	Suitable for testing and tuning of optical systems (LiDAR, cameras), vision algorithms, and lighting scenarios. Used for end-to-end testing of target detection, pose estimation, approach strategies, and simulated capture using robotic arms that simulate the effect of the propulsion subsystem.
Air bearing platform	Enables planar 2D motion testing of the chaser on a friction-reduced surface. Useful for testing relative navigation in 2D and in-house propulsion system in 2D.
Parabolic flight	Provides short-duration (∼20s) microgravity. Enables observations of microgravity dynamics and validation of in-house propulsion subsystem (behavior, stability, controllability).
Space Station (e.g. ISS)	Final demonstration platform for end-to-end autonomous mission execution in microgravity. Validates integrated system performance.

Table 3.2: *Overview of Testing environments*

3.3.1 Dark Room

The dark room is a specialized testing facility that ClearSpace has developed in its basement, and is designed for hardware-in-the-loop simulation of proximity operations. The room features black-out walls, floor, and ceiling, and is equipped with a 7.5-meter linear KUKA KL100 rail carrying two KUKA KR10 R1100-2 robotic arms. One robotic arm can be used to mount the payload, e.g. vision sensors such as LiDAR, RGB cameras, while the second arm can be used to mount the mock-up client. This setup allows for relative motion between the chaser and client, simulating 6DoF maneuvers. The facility is particularly well-suited for validating algorithms from CVLab, CSEM, and ClearSpace, and serves as a critical de-risking platform prior to ISS deployment.

Parameter	Value / Constraint
Room Dimensions	9 m (L) × 6 m (W) × 2.5 m (H)
Usable Rail Length	7.5 m
Robotic Arms	2 × KUKA KR10 R1100-2
Rail Model	KUKA KL100
Payload Mounting Options	One arm supports sensors/capture system; one arm simulates client
Environment	Fully enclosed, black-out room (low-light / controlled lighting)
Applications	Sensor calibration, LiDAR testing, relnav algorithm validation

Table 3.3: *Constraints and Capabilities of the Dark Room Test Facility*

3.3.2 Parabolic flight

Parabolic flights are a widely used method to simulate microgravity conditions on Earth. During such a flight, the aircraft (typically an Airbus A310 operated by Novespace for ESA campaigns) follows a series of parabolic trajectories, each producing approximately 20 seconds of weightlessness. Each parabola lasts approximately 70 seconds (20 seconds at 1.8 g + 3 to 5 seconds of transition

+ 20 seconds of weightlessness + 3 to 5 seconds of transition + 20 seconds at 1.8 g), followed by a 110 second period at steady level 1 g flight (see figure 3.3). [1] [2] [3]

Longer breaks are scheduled between sets to allow for experiment setup modifications. Typically, the first few parabolas are reserved for crew adaptation and calibration, accounting for human error and in-flight learning. A standard ESA campaign spans one week and includes three flights over that week, each featuring up to 31 parabolas executed in sets of five. Entry into such a campaign is coordinated through ESA: prospective experimenters submit a proposal and, if selected, receive technical and logistical guidance for flight implementation.

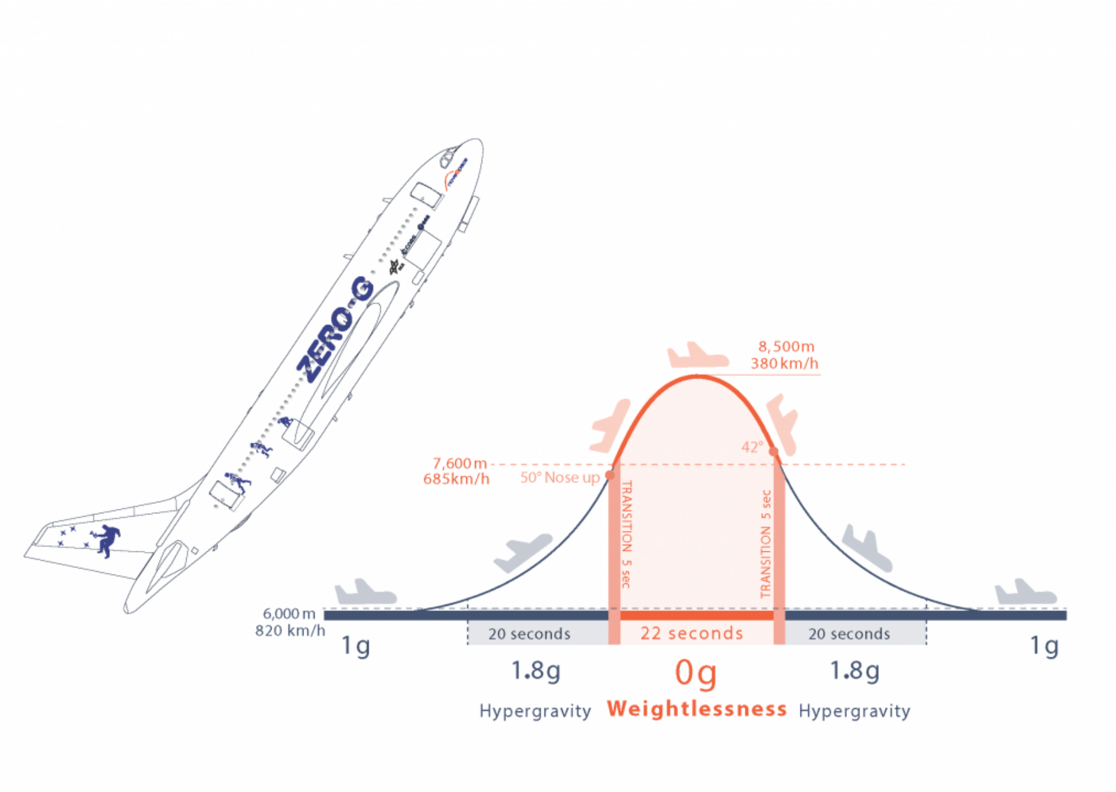


Figure 3.3: *Parabola of Air-Zero-G of the NoveSpace Campaign*

The figure 3.4 shows the inner cabin dimensions for conducting experiments in the Airbus A310 operated by Novespace, and the table 3.4 shows the main constraints of such a flight.

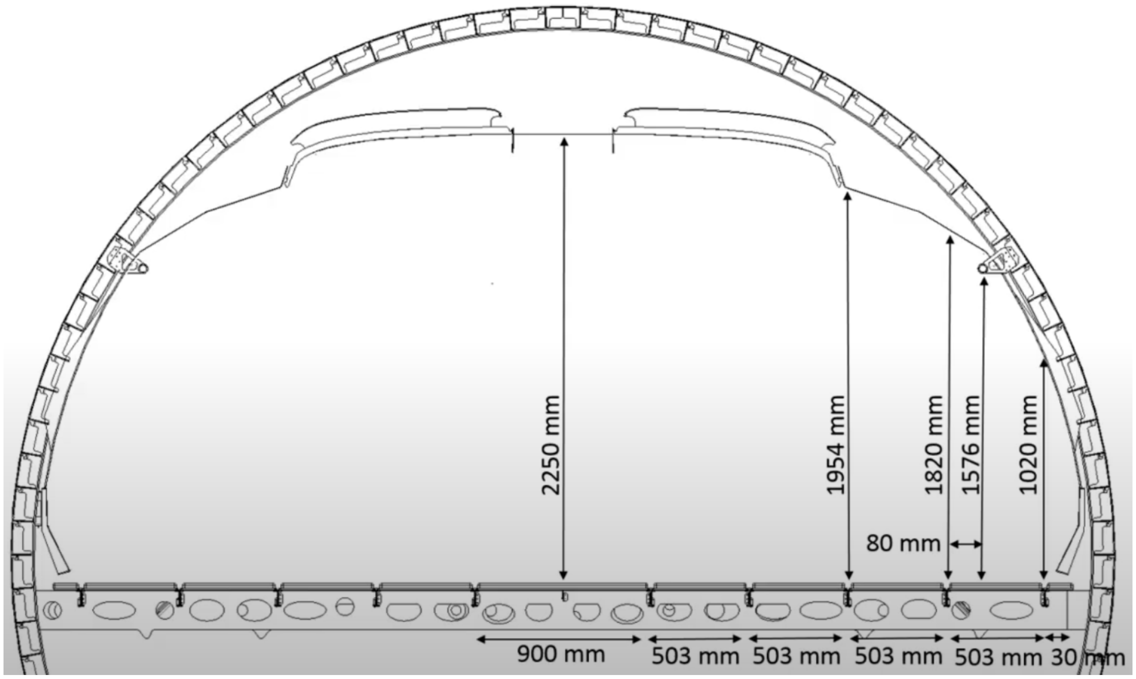


Figure 3.4: *Cabin Dimensions of Air-Zero-G Parabolic Flight*
[4]

Category	Constraints
Schedule	Experiment gets accepted 9-10 months in before flight and proposal needs to be sent in before that. It is recommended to send in the proposal at least 12-14 months before the parabolic flight.
Length of Weightlessness (0g)	22s per parabola, accounting for 1-2 seconds of transition between phases
Weightlessness accuracy	0 g ± 0,02 g in Jx, ± 0,01g in Jy, ± 0,03 g in Jz.
Hypergravity	1.8 g for 20s (c.f. figure 3.3)
Setup Time	2 minutes between parabolas
Volume of experiment	< 2m × 2m × 2.25m
Equipment Mass	Total equipment should be <20kg; free-floaters should be <10kg
Aircraft loading Door	1.80m (H) × 1.07m (W)
Cabin Luminosity	600 lux
Number of crewmen	40 in total per flight, 2 per experiment for the handling of the experiment. It is recommended that the mechanical set-up should be prepared by a professional workshop technician.
Power Supply	230V AC; max. 2–3.5 kW (depending on setup)
Noise Environment	70-75 dBA during weightlessness, 80-88 dBA during hypergravity phases
Free-Floating Modules	Use tether, cage, netting or some other method of restraining the free floating modules
Cabin Pressure	825 ± 5 hPa
Cabin Temperature	17–25°C
Cabin Humidity	Can go up to ∼15 %
Batteries	COTS pre-certified batteries, strongly discouraged to build our own custom battery system
Things to avoid	Combustion, radioactive, lasers >= 1M, lithium batteries for free-floating modules (non-COTS), GMO, X-ray, electromagnets, toxic/explosives, extreme magnetic fields, high voltages or high electrical power.
Pressurized equipment	pressure × volume < than 4 L.bar
Equipment temperature	liquids <49°C, materials <60°C
High energy system	It is recommended to avoid high-energy systems (centrifuge, flywheel, springs, ...)
Liquid	The total liquid quantity within an experiment should remain within 0.5 L, and double sealed containers should be used.

Table 3.4: *Air-Zero-G Parabolic Flight Constraints*

For more detailed compliance and requirements regarding the NoveSpace Parabolic Flight, that is going to be relevant in later phases, the following documents are essential references:

- RQ-2014-6_Requirements_EN
- GDL-2014-6_Guidelines_EN
- ITF-2014-5-Interfaces_EN
- Template Experiment Description: ESDP-2023-01-Experiment_Safety_Data_Package-EN

3.3.3 ISS

The following constraints summarize the most relevant phase 0 environmental, safety, and integration constraints for conducting experiments inside the Columbus module of the ISS. These are intended to guide early-phase design decisions and help identify critical limitations for the development of the PrOXISS mission. While detailed safety documentation (e.g. SSP 57000 [5], SSP 51721, SSP 30599) exists, it is not necessary to review these in full at this stage. Key elements most applicable to the PrOXISS mission are outlined below.

The PrOXISS payload is intended to operate as a centre aisle **stand-alone payload**, not mounted to any standardized rack such as the European Drawer Rack. This allows flexible placement within the Columbus module, provided all safety, volume, and power constraints are respected. As a general guideline, stand-alone payloads are roughly the size of a large shoebox, but larger volumes can be accepted if justified and safely contained. The payload is transported and stored in a cargo transfer bag. Cargo transfer bags are available in different sizes, and so it is not a driving design constraint at this stage.

Although the payload will operate in microgravity, the environmental conditions in Columbus are stable and close to Earth-like conditions($\sim$ 1 bar, 20°C). Ground monitoring and teleoperations are expected to be supported via CADMOS in Toulouse, France, where most of the robotic and stand alone payloads are monitored.

It is important to note that, if selected, the project will be assigned an ESA Payload Engineer who will provide detailed technical and safety guidance in future phases. Experiment planning must also align with the astronaut mission window (in this case, ESA astronaut Marco Sieber), currently estimated between 2027 and 2029, which is subject to change based on launch schedules and ISS operations.

For more detailed compliance and requirements regarding the ISS, that is going to be relevant in later phases, the following documents are essential references:

- SSP 57000 – Pressurized Payloads Interface Requirements Document
- SSP 51721 – ISS Safety Requirements
- SSP 30599 – Safety Review Process

Category	Constraint
Schedule	Marco Sieber's Mission: somewhere between 2027 and 2029
Microgravity	0g ± 0.2 g: "Payloads should provide positive margins of safety for on-orbit loads of 0.2 g acting in any direction." (SSP5700)
Internal Volume of Columbus	1.8 × 1.8 × 3.2 m3
Volume for transportation and storage	Must fit in Cargo Transfer Bag (available in different sizes), is quite adaptive to the payload
Pressure	979–1027 hPa
Lighting of environment	108 lux
Propulsion	Must be safe & low-disturbance (see below for main constraints about rotational parts); No chemical
Microgravity Disturbance	Payloads that generate a microgravity disturbance shall limit force applied to the ISS over any ten-second period to an impulse of no greater than 10 lb·s (44.5 N·s).
Power	28V DC, 10A (cooling through air from columbus module); USB 2.0 power outlets (5VDC, 500mA)
Batteries	COTS pre-certified batteries recommended
Battery Charging	Allowed (crew time required); must be ISS-compliant
Handling and Mechanical Safety	Cubesat must be easy to retrieve and manipulate manually by an astronaut. Any free-floating equipment shall not have loose parts or sharp edges (safety against impacts e.g. foam on corners)
Surface temperature of payload	Surface temperature should be <45°C and >4°C.
Status light indicators	Status light should be present, flashing lights should be avoided
Data & Comms	Must comply with RF rules: MPCC/Ethernet LAN via secure communication IP protocols (SFTP or SSH). See below for more information about data and communication protocols.
Temperature of Columbus Module	18.3–26.7°C (nominal ∼ 22°C)
Humidity	25–75%; Dew point: 4.4–15.6°C
Atmosphere	24% O2 / 78% N; Max O2: 24.1%; Max N2: 800 hPa
Ventilation of Columbus Module	0.051–0.203 m/s
Radiation	Up to 30 Rads(Si)/year
Materials	Must pass flammability, toxicity, and off-gassing standards (see below for main constraints and requirements regarding materials).

The materials are most likely the most restricting and maybe the most surprising point to be considered. Although ISS flies a lot of COTS equipment, there are some restrictions forcing projects to analyze and often to modify COTS equipment before it can be flown. Payloads must avoid the use of materials that are flammable, toxic, or prone to off-gassing, in accordance with standards such as NASA-STD-6001B and ECSS-Q-ST-70-29. Moreover, a Structural Verification Plan and a Fracture Control Plan need to be prepared and approved by ESA before the Phase B Safety Review closure.

Forbidden Materials:
The following materials constitute a hazard and are prohibited from being used without prior approval from ESA: beryllium (for structures), beryllium oxide, mercury, cadmium, lithium, magnesium, zinc, polyvinyl chloride (PVC), radioactive materials, polyamide insulated cables. Note:

'normal' Ethernet or USB cables are not allowed(!) because they contain PVC or Polyamide. Also internal cables often fall into the 'forbidden' category and need to be replaced e.g. by LSZH (Low Smoke Zero Halogen) cables.

Materials off-gassing:
Any gas released into the cable atmosphere would accumulate in there over time and could potentially become toxic. Therefore off-gassing needs to be avoided. ESA/NASA consider the concentration after seven days of exposure (Seven-day Spacecraft Maximum Allowable Concentrations SMAC). All materials used/launched/stored in habitable flight compartment shall meet the off-gassing requirements of NASA-STD-6001B or ECSS-Q-70-29. Determination of off-gassing products from materials and assembled articles shall meet the off-gassing acceptance criteria in paragraph 7.7.3 of NASA-STD-6001B. Sometimes the off-gassing characteristics of a material is not known or the manufacturer doesn't make the data available. A vacuum test may be necessary to find out if the materials off-gas.

Materials flammability:
Fire extinguishers are not really an option. Materials shall ideally not be flammable. When flammable materials are used in quantities larger than allowed, a method to control the flame propagation shall be agreed with ESA (with safety). Materials flammability shall be tested in accordance to Test 1 (Upward Flame Propagation) of NASA-STD-6001B Appendix A.2.4 or Test 1 (Upward Propagation Test Method) of ECSS-Q-70-21 or Test 4 of ECSS-Q-ST-70-21. Electrical wire insulation shall be tested for flammability in accordance to NASA-STD-6001B Test 4 or ECSS-Q-ST-70-21 Test 3 (Electrical Wire Insulation Flammability Test Method). Electrical wire insulation for arc tracking shall be evaluated by test or analysis with a method to be agreed by ESA (safety). Flammable material may be used for a short time in the pressurized environment but they have to permanently stowed in non-flammable containers. Details on their handling has to be agreed with ESA safety during the operations preparation.

Fluid Compability:
All materials shall be evaluated by analysis for compatibility with applicable liquids or gasses. Materials exposed to corrosive or hazardous fluids shall be evaluated by analysis or tested for compatibility. Materials compatibility with liquid and gaseous oxygen shall be evaluated in accordance to NASASTD-6001B paragraph 6.3

Shatterable materials:
Shatterable materials shall be contained such that 50 micron or larger particles are not liberated in the cabin. Shatterable materials shall not be stressed (no delta pressure). Camera lenses shall be recessed, supervised by the crew when in use, and placed in protected storage or contained when not in use. The ESRP may require that payloads with shatterable materials are subject to vibration test at flight levels followed by visual inspection.

Rotating Equipment
Payload's rotating parts shall be contained. The rotating parts shall not exceed 200 mm (8 inches) in diameter and 8000 revolutions per minute (rpm) speed in all conditions. Unique controls are required for rotating parts exceeding 200 mm and 8000 RPM and shall be documented in a Unique Hazard Report. Obvious containment capability is considered acceptable for computer Hard Disks whose structure/enclosure is unmodified and that are industry/safety certified (Example: UL, IEC, CE ratings).

Pressure relief valves
Payloads using relief valves shall be designed such as a periodic re-test of the valves is possible once the payload is on board ISS. Alternatively, the payload shall:

- use overpressure protections that do not require periodic retest, such as a burst disc;
- use relief valve with a threaded fitting and upstream pressure isolation that can easily be replaced;

- provide overpressure protection that can be retested in-place;
- provide overpressure protection that can be manually verified periodically in-place (relief valve with a manually opening device).

Soldering and Circuit Boards
There are no requirements concerning soldering. But we always recommend to use conformal coating for all PCBs. This prevents the release of toxic components into the cabin air and also provides additional mechanical fixation for the components. Heavy components should be glued to the PCB to better protect the components during launch. Vibration loads are not be underestimated even if small experiment payloads are launched soft-stowed and in bubble wrap.

3.3.4 Other Constraints

Constraint	**Description**
ISS Crew Time Constraints	Based on feedback from the SSO, the originally proposed 80 hours of crew interaction is considered excessive. Hands-on operations should be minimized.
Need for ISS Justification	The SSO strongly recommends demonstrating that the ISS is uniquely suited for this experiment to justify mission relevance.
Funding Limitations	May constrain spacecraft and mission design, or access to testing platforms (e.g., not permitting parabolic flight campaign).
Export Control	Must avoid restricted components or comply with relevant Swiss, EU, and/or US export regulations.
Institutional Access	Shared facilities (e.g., cleanroom, dark room, robotics labs) have limited availability and may require reservation or prior approval.
Political Considerations	Geopolitical shifts or changes in agency priorities may impact funding, scheduling, or experiment approval.
Legal Agreements	Required between institutions or companies to formalize collaboration and exchange hardware, intellectual property, or sensitive data.

Table 3.5: *Other Constraints Relevant to PrOXISS*

4 Functional analysis

The chaser function tree is represented below in Fig.4.1. It highlights the main high level functions it shall do.

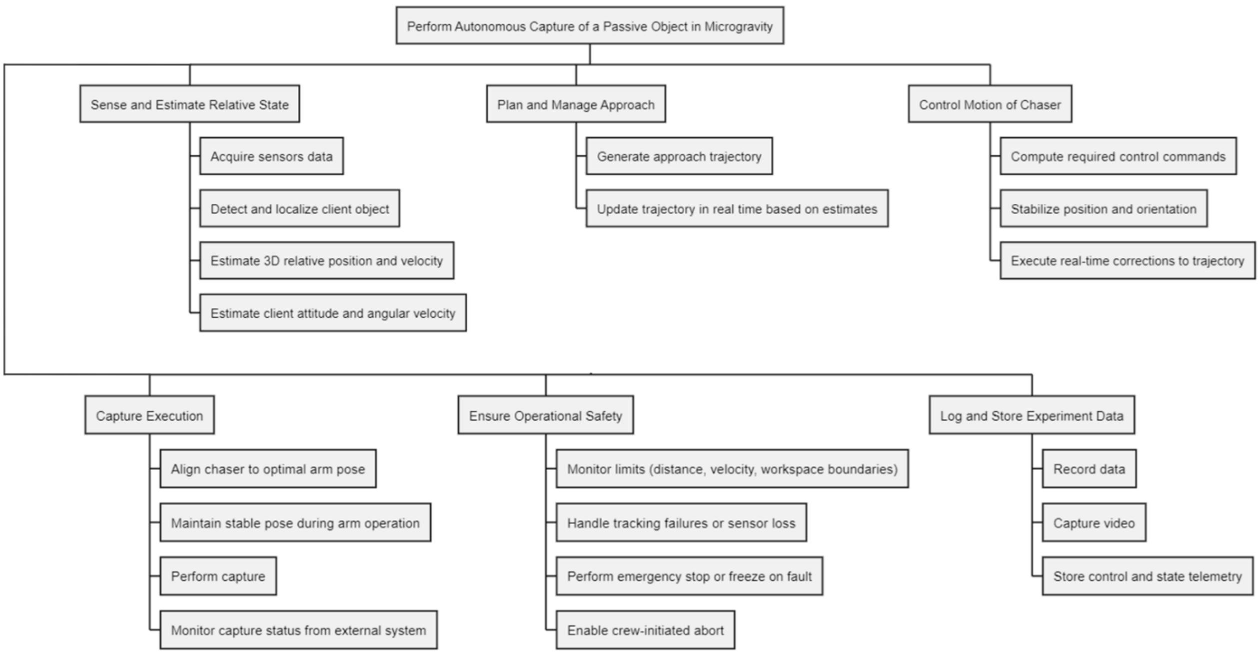


Figure 4.1: *Function tree*

5 Requirements

The following system requirements have been derived directly from the previously defined stakeholder expectations and the technical, operational, and safety constraints outlined in the preceding section. They serve as a foundational input to guide the design, verification, and implementation phases of the PrOXISS mission. While a complete and structured list of all requirements can be found in the Appendix A, this section highlights the most important requirements for this project. [5]

ID	Title	Description
High Level Requirements		
MIS.001	Declaration of Purpose	The mission shall test techniques and strategies for capturing uncooperative objects in microgravity.
MIS.002	Testing in a Microgravity Environment	The experiment shall be conducted in microgravity to simulate space-like conditions for testing.
MIS.003	Safe and Controlled Experimentation	The experiment shall be conducted in a manner that allows resets after failed operations.
MIS.004	Use of a Robotic Chaser Spacecraft	The experiment shall utilize a small robotic chaser spacecraft for proximity operations and client capture.
MIS.005	Use of a Tracking System	A tracking system shall be used to monitor the experiment's execution and collect performance data.
MIS.006	Multi-Scenario Testing Capability	The experiment shall allow for various clients shapes, sizes, and initial conditions.
MIS.007	Public Outreach Consideration	The mission shall take into consideration public outreach and educational activities.
ISS		
ISS.001	ISS Compliance	The mission shall comply to all ISS, ESA and ground station reglementations and requirements
ISS.002	Microgravity	The spacecraft and all its subsystems shall be able to operate under microgravity conditions (0 g $\pm$ 0.2 g (any direction))
ISS.003	Volume available for experiment	The experiment shall be conducted inside a volume of 1.6*1.6*3 m^3
ISS.007	Battery Safety	Only COTS pre-certified batteries shall be used.
ISS.009	Handling Safety	The spacecraft must be easy to retrieve and manipulate manually by an ISS crewman. Any free-floating equipment shall not have loose parts or sharp edges (safety against impacts e.g. foam on corners). There shall be no parts that get loose or break at any time.
ISS.028	Rotating Components	All rotating elements must be enclosed and remain below 200 mm in diameter and 8000 rpm in all conditions, unless safety-assessed.
Parabolic Flight		
FLI.006	Dimensional Constraints of experiment runs	The experiment equipment shall be sized under 2*2*2.25 m^3 (length*width*height)
FLI.007	Dimensional Constraints of equipment	The experiment equipment shall be loadable through a 1.80*1.07 m^2 door.

Continued on next page

ID	Title	Description
FLI.009	Mass of Free-Floaters	Free-floating modules should have a mass <10 kg.
FLI.010	Restraining of Free-Floaters	Free-floating modules should be restrained (e.g., cage, tether, netted area).
FLI.011	Mass of equipment	Each equipment or payload assembly should have a mass <20kg.
MTS.001	Ground Truth	ISS Cameras: Ground truth video data shall be captured by cameras and downlinked post-experiment
MTS.002	Marker System	Visual markers (such as ArUco markers) should be affixed to WILL and the target to support visual pose estimation
Spacecraft		
SC.004	Spacecraft Mass	The spacecraft mass shall not exceed 10 kg
SC.006	Body volume	The spacecraft body (without the capture system) shall fit in a 200*200*200 mm^3 cube.
SC.007	Spacecraft DoF	The spacecraft shall have 6 DoF.
SC.008	Spacecraft Linear Acceleration	The spacecraft maximum linear acceleration along each axis shall be at least 0.5 cm/s^2.
SC.009	Spacecraft Angular Acceleration	The spacecraft maximum angular acceleration around each axis shall be at least 0.3 deg/s^2.
SC.010	Spacecraft Maximal Velocity	The spacecraft maximum velocity shall be at least 0.05 m/s.
SC.012	Capture system	The spacecraft shall have a capture system to capture client object
SC.013	LiDAR	The spacecraft shall have a Lidar to detect the client object
SC.014	Navigation algorithm	The spacecraft shall support the implementation of real-time navigation algorithm
Payload		
PL.001	Capture system mass	The capture system mass shall not exceed 2 kg.
PL.002	Capture system power	The capture system power consumption shall not exceed 50 W.
PL.003	Capture system size	The capture system shall fit in a hemisphere defined by base of 700*700*100 mm^3 to 300*100*100 mm^3 at top.
PL.004	Client object size	The client object size shall be 100*100*100 [±20*20*20] mm^3.
PL.005	Client object mass	The client object mass shall not exceed 1/3 of the mass of the spacecraft.
PL.006	Client object relative velocity	The client object relative velocity from the spacecraft shall not exceed 0.05 m/s.
PL.007	Client object tumbling rate	The client object tumbling rate shall not exceed 5 deg/s.
PL.008	Client object shape	The client object shape shall be variable, i.e. it can be a sphere, a cube, and have optionnal removable protusions (antennas, baffle, array mockups).
PL.009	LiDAR range	The LiDAR shall be able to acquire 3D images up to a distance of 5 m.
PL.010	LiDAR accuracy	The LiDAR 3-sigma ranging accuracy shall be less than 0.01 m on the entire range.

Continued on next page

ID	Title	Description
PL.011	LiDAR update frequency	The LiDAR shall update the measurements at at least 5 Hz
PL.012	LiDAR mass	The LiDAR mass shall not exceed 1.5 kg.
PL.013	LiDAR size	The LiDAR shall fit in a volume of 100*100*100 mm^3.
PL.014	LiDAR power	The LiDAR mean power consumption shall not exceed 30 W.
PL.015	LiDAR luminosity	The LiDAR shall be able to acquire 3D images in an environment where the luminosity is 108 lux and 600 lux.
PL.016	Computer Vision Algorithms and Navigation Algorithms	The onboard real navigation algorithm shall compute 6-DOF pose estimates in real time using LiDAR data
Propulsion		
PROP.001	Purpose	The propulsion subsystem shall enable the spacecraft to move in space with 6 degrees of freedom (DOF)

Table 5.1: *Requirements*

6 Concept of Operations

The following Concept of Operations (ConOps) outlines the proposed sequence of experiments and operational logic for the PrOXISS mission, one for the parabolic flight and one for the ISS. Although these two different ConOps share the same three steps, they differ in the rest of the experiment sequences, due to environmental constraints.

This draft has been developed in collaboration with the main stakeholders and reflects a shared understanding of how the technology demonstration in microgravity is expected to proceed. At this stage, the ConOps focuses on the core mission: demonstrating the autonomous identification, approach, and capture of an uncooperative target in a microgravity environment. Secondary objectives, such as virtual reality live-streaming or remote control functionalities, are not included in this version and may be integrated later upon proposal acceptance. This draft does not yet define performance metrics (Measures of Performance) or the initial conditions for the chaser and client systems. These parameters should be further refined as soon as possible.

The parabolic flight campaign is currently considered primarily as a means to validate the in-house propulsion subsystem and observe basic free-floating behavior in microgravity. Should the project opt to use Astrobee as an external propulsion system/AOCS, this parabolic flight campaign may no longer be necessary.

Additionally, the dark room test facility, equipped with robotic arms and a linear rail, will be used on the ground to validate key subsystems such as the LiDAR, cameras, and computer vision algorithms pre-launch, according to verification plan. This setup allows for realistic relative motion between a mock client and the chaser payload, enabling early de-risking of the sensing and navigation pipeline under controlled conditions before microgravity deployment.

The experimental sequences of the ConOps in this document have been structured to closely mirror the ConOps of the ClearSpace-1 mission (c.f. figure 6.1). The ConOps presented in this paper also adapts the terminology used by ClearSpace for approach strategies in space (c.f. figure 6.2 and 6.3).

- At the **Initial Proximity Point (IPP)**, the chaser spacecraft detects and identifies the client's position, orientation, relative speed and tumbling rate. It then simulates the approach strategy to capture the Client. Starting at the IPP, the chaser performs a motion synchronisation trajectory (if the client is tumbling), which determines the type of trajectory that the chaser will make towards the client, depending on the client's parameters. At the very end of this trajectory, when the chaser has synchronized its relative movement to the client for ideal capture, the chaser reaches the final approach point .
- Starting from the **Final Approach Point (FAP)**, the chaser does a v-bar trajectory (straight line) towards the client, until it triggers the closing point.
- The **Enclosure or Closing Point** can be triggered by the disruption of a light beam between the tips of the capture system, or by a reached distance detected by the LiDAR, for example. The closing point trigger makes the capture system begin to actuate in order to enclose the client.
- The **Capture Point** is reached when the client is captured. Ideally, the capture system captures the client in an enclosed volume (a volume defined by the impossible escape of the client) before the client touches the capture system. When the capture is confirmed, the rigid stack stabilizes to achieve a stable attitude.
- **Rigid stack** is the term used for the new body that is formed when the chaser captures the client. This body has new characteristics such as new mass, new moment of inertia, etc.

Note that, if the experiment environments do not allow the chaser to perform Motion Synchronization, the experiment most likely starts from the FAP.

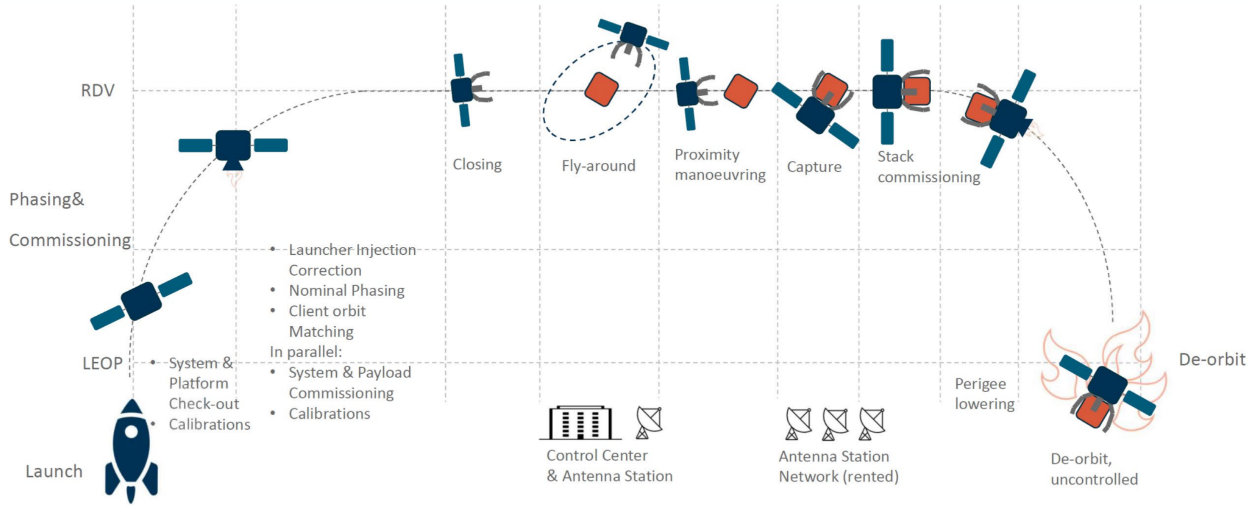


Figure 6.1: *ConOps of ClearSpace-1 Mission*
[6]

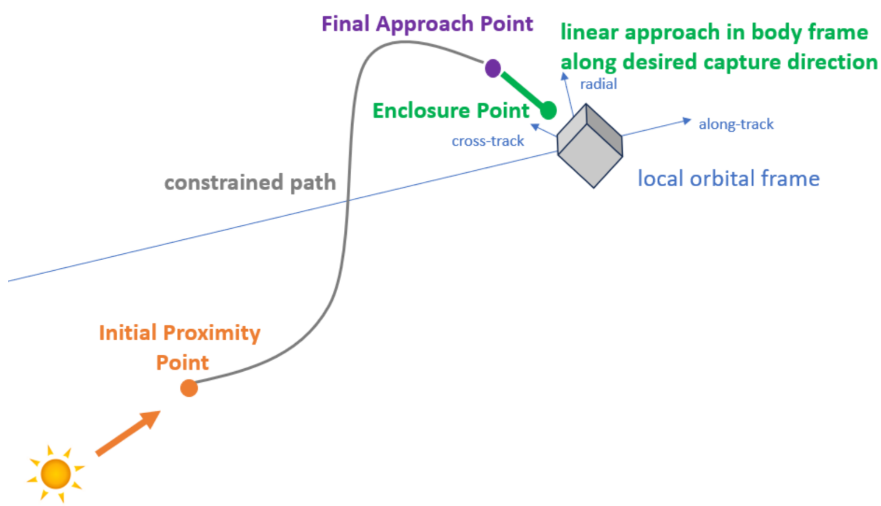


Figure 6.2: *Approach Terminology*
[6]

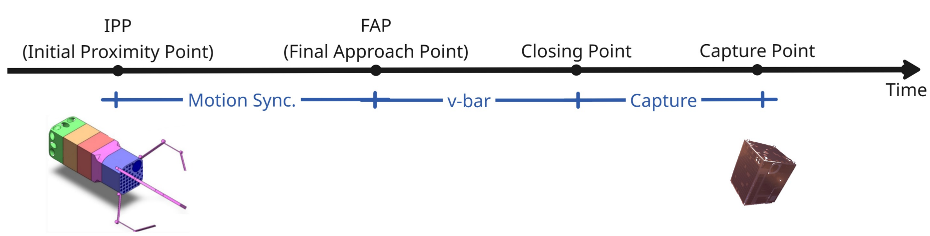


Figure 6.3: *Representative Approach Schematic and Terminology*

6.1 Parabolic Flight

On the parabolic flight, each parabola lasts approx. 20 seconds, meaning every experiment sequence must be executable within this timeframe. A total of 30 parabolas are available on a NoveSpace Parabolic Flight. To account for potential human and other errors, **each experiment sequence is**

planned to be repeated over at least 5 parabolas. This approach is based on expert recommendations suggesting that at least five parabolas per objective are necessary for maximizing feasibility. Moreover, experts advise to account for a few parabolas for the human to get used to the microgravity effects. This gives the opportunity for a maximum number of $\sim$ 5 objectives / experiments to be run during one Parabolic Flight. The objectives are structured so they can be executed independently.

It is important to note that a physical client is not required for the v-bar approach sequence during the parabolic flight, as the **main focus is on validating the propulsion system's control and maneuvering capabilities.** However, a client mock-up may still be introduced in other sequences to **observe its behavior in microgravity and assess free-floating dynamics.**

Assumption 1: the propulsion subsystem can provide us with a linear acceleration and deceleration of 0.5 cm/s^2 and a maximal constant speed of 5 cm/s. Due to time constraints ($\sim$ 20 seconds of microgravity), the v-bar trajectory is thus composed of maximum: an acceleration (max. 0.25 m, 10 sec), and a deceleration (max. 0.25 m, 10 sec).

Assumption 2: Capture System takes in average 10 seconds to close and 10 seconds to open.

Step	**Experiment Sequence**	**Description**
1	Client behaviour	Observe dynamic behaviour of client in microgravity (how does it rotate, how does it changes). These measurements can be done by either by putting sensors (e.g. IMU) on the client (recommended), by observing the client externally, or another way.
2	Demonstrate 6 DOF + chaser behaviour	1. Control the spacecraft when floating freely in microgravity and demonstrate 6 dof agility. 2. Collect data about the dynamic behaviour of the chaser in response to propulsion system.
3	De-risking exercices of Capture System	1. Close capture system while the spacecraft controls its stability ($\sim$10 seconds). 2. Open capture system while the spacecraft controls its stability ($\sim$10 seconds).
4	V-bar approach (from FAP to closing point) with no client	Chaser moves in a v-bar trajectory (straight line) from a point A to a point B, to simulate a v-bar trajectory from FAP to a symbolic closing point. The closing point is defined as the point it reaches after having travelled a given distance (e.g. <0.5m). Capture system is open during whole operation. The chaser comes to a complete stop after the desired trajectory/distance.
5	Rigid Stack Control + chaser behaviour	A client mass is then introduced to form a combined system. This is typically done during the 1g phases: the capture system is opened, the client is manually inserted into its volume, and then the capture system is closed around the client to simulate a capture event. Alternatively, a weight can be strapped or attached to the chaser to replicate the dynamics of a captured object. Once this "rigid stack" is formed, the chaser must autonomously adapt to the new center of mass and moment of inertia, and stabilize itself to maintain controlled free-floating behavior. Another way to measure the behaviour of the chaser and the propulsion control system in microgravity: the chaser begins in a free-floating and stable configuration. After a few seconds, when the chaser is shown to be stable, it can be disturbed by, for example, giving a manual push on the spacecraft. The response is then measured with on-board sensors.

Table 6.1: *Parabolic Flight ConOps*

6.2 ISS

The ISS environment, particularly the Columbus module, offers a suitable microgravity environment for demonstrating the full sequence of proximity operations and enabling technology validation that cannot be replicated on Earth or during parabolic flights.

If the project chooses to work with an external AOCS such as Astrobee, the validation of 6-DOF maneuvering (Step 2 of the ConOps) becomes primarily a de-risking exercise to confirm the reliable interfacing between the payload and Astrobee.

Given that astronaut crew time is a constrained and valuable resource, some mitigations are introduced in order to reduce crewtime. First, the stakeholders can chose not to conduct the conops with various different clients and instead, only focusing on one client. After that, if crewtime further needs to be reduced, Step 1 and step 5 can be made optional.

Additionally, it is worth noting that the initial conditions required for Step 7 (client rotating $<5°/s$ along a precise axis) may be challenging to achieve precisely in practice. At present, it is assumed that an astronaut will manually initiate the client with sufficient accuracy, but this assumption should be validated or supported with dedicated procedures or auxiliary tools in future phases.

A key operational challenge is ensuring proper initial conditions of the client, such as being stationary or rotating below 5°/s. At the moment, it is assumed that an astronaut can manually ensure these conditions properly and with enough accuracy.

Assumption: the propulsion system (whether in-house propulsion or Astrobee) can provide us with a linear acceleration and deceleration of 0.5 cm/s^2m a maximal linear speed of 5 cm/s. The maximum length of the experiment is 3 m (a bit less than the length of Columbus Module). The recommended distance between FAP and Closing/Capture Point is therefore 1.5 m.

Thus, the v-bar trajectory is composed of:
- an acceleration (0.25m, 10 sec),
- a constant speed (max. 1m, 20 sec), and
- a deceleration (0.25m, 10 sec)

The indications in red can be rediscussed and reevaluated with the stakeholders.

Step	Experiment Sequence	Description
1	Client behaviour	Observe dynamic behaviour of client in microgravity (how does it rotate, how does it changes). These measurements can be done by either by putting sensors (e.g. IMU) on the client (recommended), by observing the client externally, or another way.
2	Demonstrate 6 DOF + chaser behaviour	1. Control the spacecraft when floating freely in microgravity and demonstrate 6 dof agility. 2. Collect data about the dynamic behaviour of the chaser in response to propulsion system.
3	De-risking exercices of Capture System	1. Close capture system while the spacecraft controls its stability (∼10 seconds). 2. Open capture system while the spacecraft controls its stability (∼10 seconds).
4	V-bar approach capture, and rigid stack stability, with immobile client	1. The free-floating client is immobile (max. 2°/s) and is supervised by a crewman. 2. Chaser approaches the client in a v-bar trajectory, from FAP to capture point. 3. Distance between spacecraft and client is measured with the LiDAR. 4. After capture, the "rigid stack" is stabilised. 5. This experience can be repeated for different clients of various shapes and sizes (sphere, cube, etc.).
5	Manoeuvring with captured client to demonstrate rigid stack controllability	Maneuver (e.g. v-bar trajectory) with captured client in a controlled way.
6	Rate matching with rotating client	1. The client is rotating (max. 5°/s) along the axis that connects the client and the chaser. That axis should be parallel to the 3m length of the Columbus module. 2. The chaser spacecraft detects the rotation speed and direction, and matches its own rotation speed and direction to the client, so that the relative rotation rate is ∼0°/s between chaser and client.
7	Rate matching, v-bar approach and capture with rotating client	1. The client is rotating (max. 5°/s) along the axis that connects the client and the chaser. That axis should be parallel to the 3m length of the Columbus module. 2. The chaser spacecraft detects the rotation speed and direction, and matches its own rotation speed and direction to the client, so that the relative rotation rate is ∼0°/s between chaser and client. 3. Chaser approaches the client in a v-bar trajectory, while matching the client's rotation rate, from FAP to capture point. 4. Distance between spacecraft and client is measured with the LiDAR. 5. After capture, the "rigid stack" is stabilised. 6. This experience can be repeated for different clients of various shapes and sizes (sphere, cube, etc.).
8	Simulation of "Motion Synchronisation" Approach, with tumbling client	Client is tumbling up to 5°/s and the chaser simulates the trajectory it would take from IPP to Closing/Capture Point. The system then evaluates if it is possible to do that approach trajectory within the dimensional constraints of the environment (Columbus Module: 1.6 * 1.6 * 3 m^3) . - If "GO": Trajectory from IPP to Capture point. - If "NO GO": abort approach This experiment can be repeated for various tumbling rates and directions of the client.

Table 6.2: *ISS ConOps*

6.3 Conclusion ConOps

An overview of the ConOps for the parabolic flight and the ISS is represented graphically in figure 6.4.

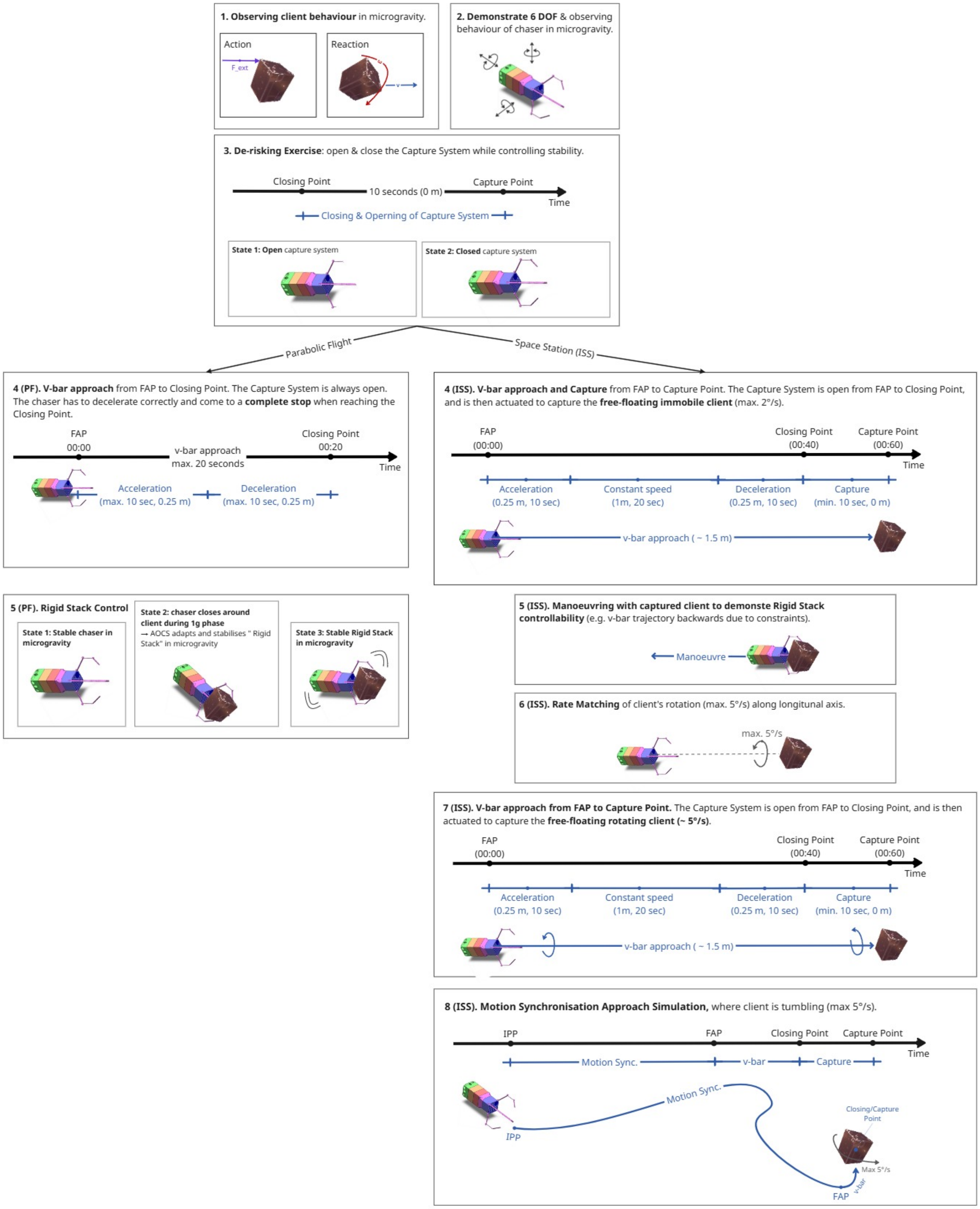


Figure 6.4: *Overview of Parabolic Flight and ISS ConOps*

7 Timeline of PrOXISS

It should be noted and kept in mind that these timelines and their milestones are highly dependent on ESA: how fast they accept the proposal, how often they give us feedback, how they plan to manage our project, when Marco Sieber's Mission will be scheduled exactly, etc.

7.1 With in-house developed propulsion system

As is depicted and explained in the ConOps, the LiDAR and vision systems are actually not being used for the experiments and validations on the parabolic flight and therefore do not have to be ready for full integration for the parabolic flight. The LiDAR and vision system can be tested on ground, parallel to the parabolic flight operations that aim to validate the propulsion system and observe the microgravity behavior. The integration of the vision system onto the chaser spacecraft can be done after the parabolic flight operations. The timeline for a project with in-house developed propulsion system can be seen in figure 7.1. The blue plane represents the begin of the parabolic flight experiments, and the green rocket represents the begin of payload integration for the launch of the payload to the ISS. The time it takes for launch integration should not be underestimated as it sometimes takes several weeks or even months.

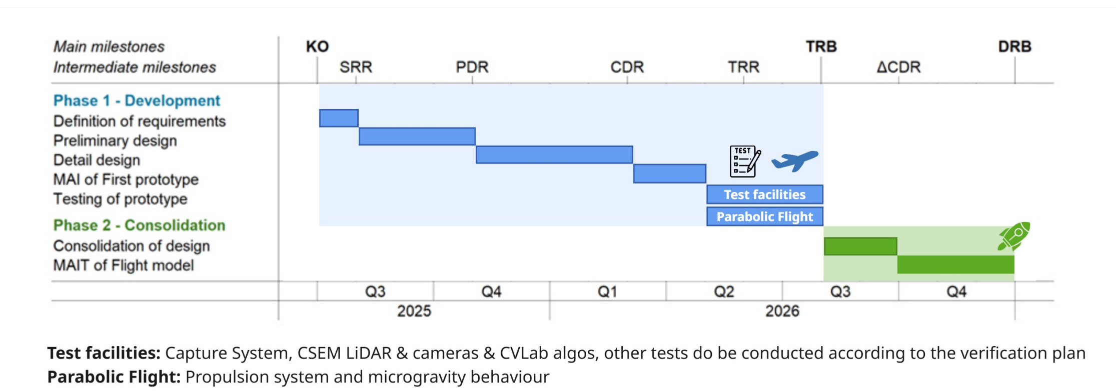


Figure 7.1: *Timeline with in-house propulsion*

7.2 With external propulsion system

With an external and outsourced propulsion/AOCS system (e.g. Astrobee, c.f. 9.1), the parabolic flight does not make sense anymore, as the main purpose of that flight is to validate the in-house developed propulsion subsystem. Therefore, there is no need to consolidate the design from a prototype that was intended for the parabolic flight, and the timeline allows for more time margin or a more relaxed schedule. This timeline is shown in figure 7.2. Again, the green rocket represents the launch of the payload to the ISS.

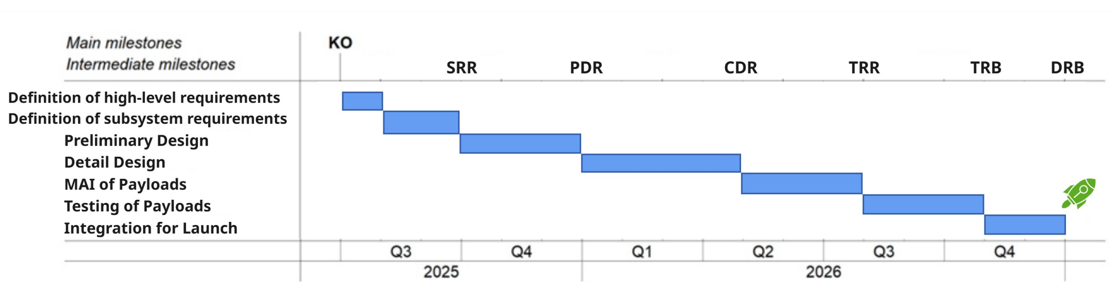


Figure 7.2: *Timeline with external propulsion system*

8 Risk Analysis

This section presents a quantitative risk analysis identifying major threats to the success of the PrOXISS mission, alongside proposed mitigation strategies. Each risk is characterized by its potential impact and likelihood, rated on a scale from 1 (low) to 5 (high) (detailed in the Appendix B). The overall risk value is computed as the product of these two factors: Risk = Impact * Likelihood. Mitigation strategies aim to reduce either the likelihood, the impact, or both, and a revised risk value is provided post-mitigation. The table below highlights the most critical risks and their associated mitigation actions, in descending order of risk. A more detailed, exhaustive risk register is provided in Appendix B.

Risk ID	Risk Description	Risk	Mitigation Strategy / Recommendation	New Risk
R.001	Unclear or incomplete requirements. Poorly defined, incomplete, or overly rigid requirements can lead to misalignment, scope creep, or insufficient system performance.	20	All stakeholders should review requirements and agree on a set of requirements that are acceptable for all stakeholders. Setup a review of requirements when important aspects of the mission changes.	3
R.004	Proposal not accepted.	20	Get in touch with SSO and ESA experts and ensure early interaction with them, communicate openly and get regular feedback on proposals. Reduce crewtime and highlight the ISS value for this project. Consult ISS, ESA and other standards and requirements early in the project. Draft a back-up plan, e.g. testing on another space station.	8
R.006	Misalignment, miscommunication and poor coordination with stakeholders, whether it is regarding timelines, budgets, bottlenecks, task repartition, etc. This can lead to misdesigns, diverging priorities and expectations among stakeholders, stakeholder conflicts, etc.	20	Organize regular meetings with all stakeholders. Use a shared platform for tracking decisions and timelines. Draft stakeholder expectations, needs, goals and objectives early on (in a feasibility study) and get an agreed and validated set of expectations that is acceptable for all stakeholders. Develop a Responsibility Assignment Matrix to clarify task ownership. Define and freeze interfaces and handovers early.	3
R.013	Crew time availability: ISS may allocate less crewtime than requested to this project.	20	Reevaluate and reduce crewtime. For example, by changing the conops, prevalidating technologies on-ground, replacing time consuming setup technologies by less consuming setups, etc. Put priorities on the experiments that are to be executed on the ISS.	8

Continued on next page

Risk ID	Risk Description	Risk	Mitigation Strategy / Recommendation	New Risk
R.017	Not adhering with PF or ISS Safety requirements.	20	Get a safety expert for the PF and an ESA ISS payload safety engineer, as early in the project as possible, that acts as adviser throughout all steps of the design and MAIT.	10
R.024	Interface incompatibility or integration impossible between payload and PF, ISS, Astrobee, or something else.	20	Review interface documents (e.g. SSP 57000). Include interface emulation in FlatSat or mock setups. Collaborate with platform providers during early phases (Get a PF expert / ISS payload specialist / Astrobee engineer). Develop interface control documents early.	4
R.002	Mismatch between project ambition and feasibility. Risk that the scope is either beyond realistic execution or too limited to justify ISS value.	16	Conduct a thorough Phase 0/A feasibility study early on to validate scope against resources. Regularly consult ESA and SSO for feedback on ISS justification and scope appropriateness. Use a progressive mission plan (e.g. break down into demonstrable steps like PF $\rightarrow$ ISS). Maintain traceability between objectives and technical capabilities.	3
R.003	Unrealistic Timeline or Delayed Milestones. Poor planning (e.g. underestimated time required for MAIT) or unforeseen delays disrupt schedule, jeopardize milestones.	16	All stakeholders should review the proposed timeline and agree on one timeline. The timeline should be detailed with the main milestones. All stakeholders should be aware of what are the deliverables for each milestone. The timeline should be reviewed and updated regularly if necessary. Moreover, build in a margin in the timeline to reduce impact.	6
R.012	Overrun of financial budget. Unexpected increases in material costs, labor expenses, or unforeseen issues can lead to budget exceedances.	16	Account for budget margins. Write out back-up plans & strategies in case there are budget exceedances. Add ”cost” as a driving design metric.	9

Table 8.1: *Risk Analysis and Mitigation Recommendations*

The two biggest risks, although decreased dramatically, now remain the following:

- Overrun of financial budget. Unexpected increases in material costs, labor expenses, or unforeseen issues can lead to budget exceedances.
- Not adhering with PF or ISS Safety requirements.

Further contingency strategies can be put into place, alongside with a solid verification plan, as this is only a preliminary preliminary risk analysis. As the project progresses, the risk analysis should be regularly revisited and refined to reflect updated.

9 System Trade-off

9.1 Astrobee

9.1.1 Introduction

As described in Section 2, Astrobee is a free-floating robot on the ISS. It can host payloads and perform experiments. It has various advantages and disadvantages for our potential utilization.

Advantages

- TRL: it is already used in the ISS and is a proven technology.
- It reduces the complexity as it takes care of several subsystems such as propulsion, power and communication.
- It facilitates the procedures to comply to the ISS standard (e.g. safety, interfaces between the spacecraft and the station, etc.)

Disadvantages

- It is a US technology, which leads to several uncertainties: Can it be uses by European companies / agencies ? Is it only in a US laboratory on the ISS ? Can it only be used by an NASA astronaut ?
- If the launch on the ISS is canceled, there is no backup solution.
- No need for a parabolic flight (can be also be an advantages as it was discussed in Section 6.1).

Documentation about Astrobee can be found in NASA resources:

- Official website [7]
- NASA IRG-FF029: Astrobee Guest Science Guide [8]
- Astrobee Systems Engineering Design Overview [9]
- Astrobee software [10]

9.1.2 Trade-off

The trade-off is made on six criteria, listed below. Each has a weight between 1 and 3, subjectively attributed, to highlight the more important criteria and not to have a criteria with minor importance be decisive in the choice. Each possibility is then graded for each criterion between 1 and 5 and the sum is made to decide the best solution, which is the one having the higher sum.

Criteria

- **Technology Readiness Level (TRL):** how much the technology is ready for the flight, i.e. the maturity of the platform (a higher TRL indicates a more mature and flight-ready technology)
- **Complexity:** how much the platform is difficult to develop, integrate and operate (the higher this metric, the lower the complexity)
- **Political:** how much the geopolitical situation and potential international partnership can influence the success of the mission (the higher this metric, the lower the impact of geopolitics)
- **Schedule:** how much the timeline from mission statement to end of operation is long (the higher this metric, the faster the timeline)
- **Resources and Support:** how much information and engineering support are available from stakeholders such as space agencies to help the mission (the higher this metric, the higher the amount of required resources)

- **Flexibility:** how easy it is to modify, adapt and reuse the platform (the higher this metric, the easier it is)

Criteria	Weight	In-house	Astrobee
TRL	*3*	1	5
Complexity	*3*	2	5
Political	*1*	5	2
Schedule	*2*	2	4
Ressources and support	*1*	1	4
Flexibility	*1*	4	2
TOTAL		**23**	**46**

Table 9.1: *Trade-off Matrix In-house vs. Astrobee*

The best solution is Astrobee. It is therefore recommended to use Astrobee. However, as mentioned before, it is only a recommendation, as other political unknowns have to be considered. If all stakeholders are *GO* for Astrobee (meaning SSO/ESA agree, payload providers agree, and if PrOXISS is accepted in the Astrobee program), it is recommended to use it, as it greatly reduces the complexity of the project and enables a higher focus on the payloads and on the core mission goal. However, if there is a *NO GO* from one stakeholder, everything can still be developed in house, but more resources will be required.

To conclude, using Astrobee has many advantages but brings its share of changes to the project. Some requirements are no longer valid, the ConOps will change a little and the timeline may be more relaxed.

Note: for the sections than follow, it is assumed that the in-house solution is chosen, as it is the solution that requires most development. It will be indicated in a note at the beginning of every section where there are differences between in-house and Astrobee.

9.2 Size and Format

Note: this section is only valid for the in-house developed solution

In the initial SSO proposal, the spacecraft was a 3U cubesat. However, during the study and the discussion with stakeholders, it appeared that it might not be the best solution. This section explains the choice of the size and format of the chaser.

9.2.1 Possibilities

3U Cubesat The first solution is a 3U Cubesat represented in Fig. 9.1. It follows the cubesat standard, allowing for COTS component compatibility. Nevertheless, it has less customization and less volume, which may complicate the integration of subsystems, especially payloads.

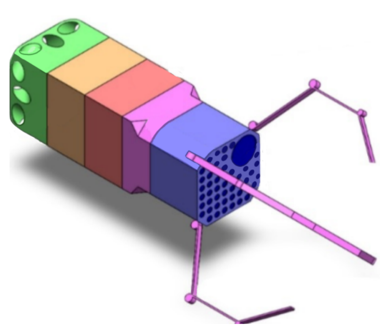


Figure 9.1: *3U Cubesat solution*

In-house 200mm Cube The second solution is a 200mm Cube as represented in Fig. 9.1. It has more layout freedom (as the subsystems do not have to be stacked in a specific way or CubeSat 3U standard), more volume is available and it allows for more flexibility. On the other hand, it will probably need more development and limit the use of CubeSat COTS parts.

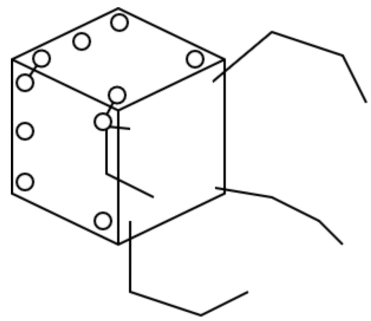


Figure 9.2: *200mm Cube solution*

9.2.2 Trade-off

The trade-off is made on six criteria, listed below. Each has a weight between 1 and 3, subjectively attributed, to highlight the more important criteria and not to have a criteria with minor importance be decisive in the choice. Each possibility is then graded for each criterion between 1 and 5 and the sum is made to decide the best solution, which is the one having the higher sum.

Criteria

- **Volume efficiency:** how much volume and how well it can be used (a higher score indicates higher efficiency)
- **Integration complexity:** how much it is difficult to integrate the subsystems (a higher score indicates and easier integration)
- **COTS Ecosystem:** how much already available components can be used (a higher score indicates more available COTS components)
- **Payload accommodation:** how easy it will be to host the payload(a higher score indicates and easier accommodation)
- **Propulsion:** how easy the propulsion subsystem will be to design (a priori estimation, a higher score indicates an easier design development)
- **Reusability:** measure the potential of reuse and upgrade (a higher score indicates that it is more reusable)

Criteria	**Weight**	**3U Cubesat**	**200mm Cube**
Volume efficiency	*2*	2	5
Integration complexity	*3*	1	5
COTS Ecosystem	*2*	5	2
Payload accommodation	*3*	3	5
Propulsion	*2*	2	4
Reusability	*1*	5	3
TOTAL		**35**	**55**

Table 9.2: *Trade-off Matrix 3U Cubesat vs 200mm Cube*

The best solution is a 200mm Cube, developed in-house. It has an easier integration and layout and a better payload accommodation. It also helps a lot the feasibility of the propulsion subsystem by allowing more possible fans thrusters placement (we will discuss more about the propulsion subsystem later in section 11.5). As we do not have many of the constraints that make the strength of the Cubesat standard (launch dispenser, space-grade components), as we are inside the ISS in a controlled environment and launching on ISS cargo bag having their own standards, the pressure to select the Cubesat standard is much lower.

10 System description

Note: This section is divided into two, each half being for each solution explored before in the trade-off (In-house and Astrobee). This enables to further detail the differences between each and already have a strong basis once the final decision will be made.

10.1 In-house

10.1.1 System Overview

The Fig.10.1 presents the layout of the In-house solution. The spacecraft is composed of a main body that contains all the subsystems, with holes distributed around it for the fan thrusters. The front face houses the LiDAR and Vision system, and the four arms of the capture system.

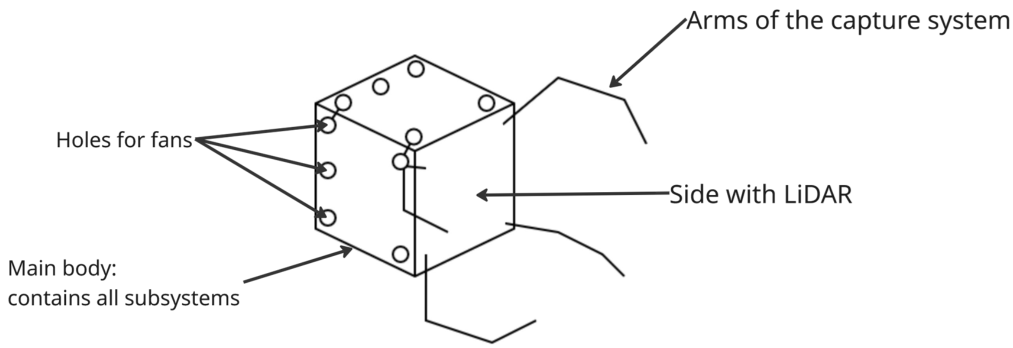


Figure 10.1: *System overview of In-house solution*

Propulsion

- Air propellers (Fans) (See Section 11.5 for details about the choice of the propulsion technology)
- Operating in the ISS atmosphere
- Pointing away from client object to avoid air flux perturbations

AOCS

- Control Attitude
- COTS Equipment

Onboard Computer (OBC) and Communication

- Modular software for easy update of algorithms
- Wireless interface to ISS

EPS

- Provide electrical power to all other subsystems

LiDAR and Vision

- Based on LiCoRIS project
- Cameras (all around the spacecraft)
- High computing power for demanding algorithms

Capture system

- Small-scale version of ClearSpace-1 capture system

10.1.2 Block diagram

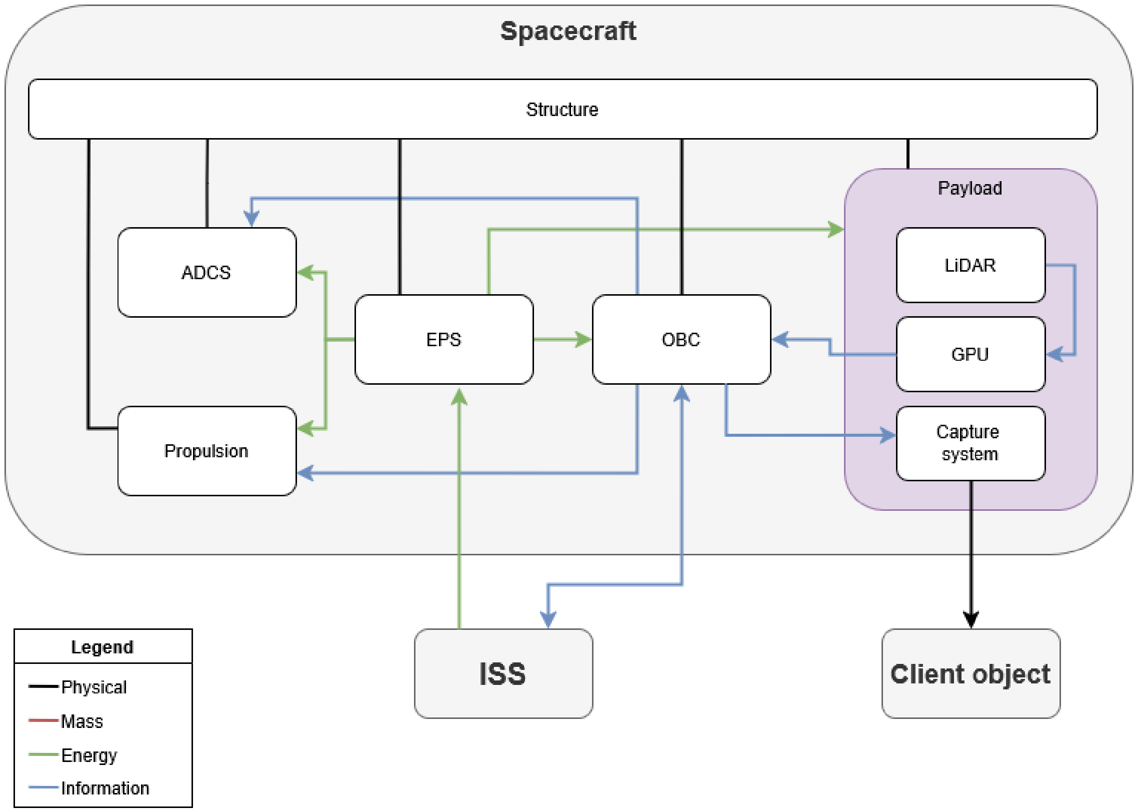


Figure 10.2: *Block diagram of In-house solution*

10.1.3 Budgets

Subsystem	**Mass [kg]**
Payload - LiDAR	1.5
Payload - GPU	0.25
Payload - Capture system	2
OBC	0.25
Communication	0.25
EPS (inc. harness)	2
AOCS	1.5
Propulsion	0.75
Structure	1.5
TOTAL	**10**

Table 10.1: *In-house solution Mass Budget*

Subsystem	Mean Power [W]	Peak Power [W]
Payload - LiDAR	30	60
Payload - GPU	40	60
Payload - Capture system	30	50
OBC	3	5
Communication	2	5
EPS (inc. harness)	2	3
AOCS	5	10
Propulsion	6	15
TOTAL	**118**	**208**

Table 10.2: *In-house solution Power Budget*

10.2 Astrobee

10.2.1 System Overview

The Fig.10.3 present the layout of the Astrobee solution. Astrobee contains the standard subsystems such as propulsion, power and communication, and has cameras and sensors that can be used. It also has payload bays for external experiments. These bays will host the paylaod which is composed of the LiDAR and Vision, capture system and a computer which will control the robot according to the ClearSpace algorithms.

Figure 10.3: *System overview of Astrobee solution (©NASA, annoted)*

LiDAR and Vision

- Based on LiCoRIS project
- Cameras
- High computing power for demanding algorithms

Capture system

- Small-scale version of ClearSpace-1 capture system

10.2.2 Block diagram

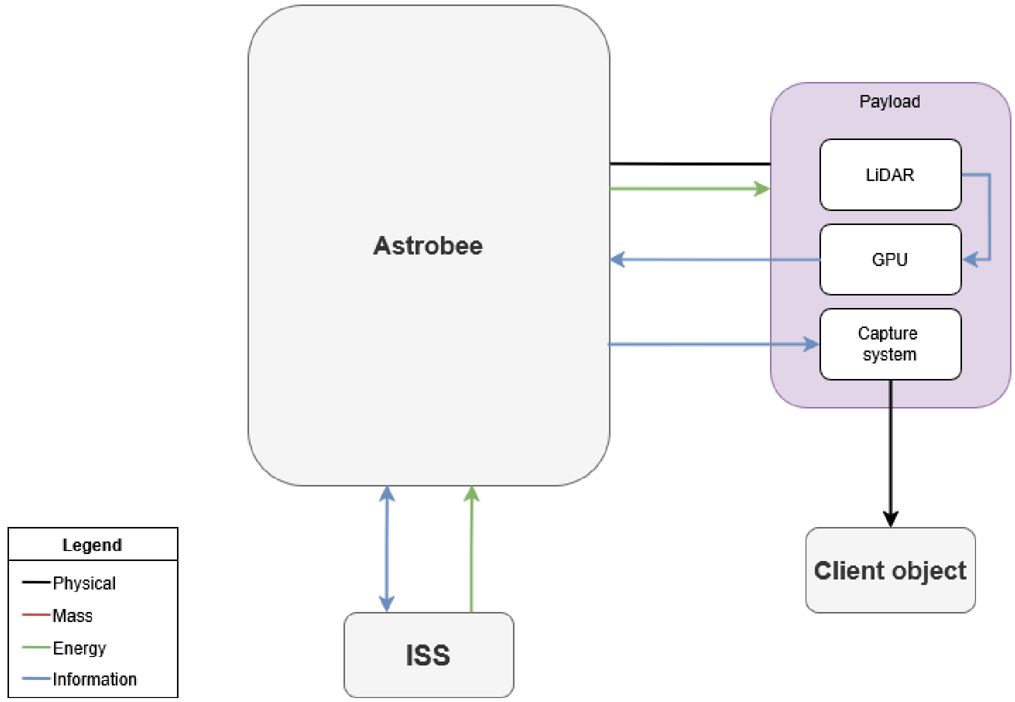


Figure 10.4: *Block diagram of Astrobee solution*

10.2.3 Budgets

These budgets are the payloads budgets, which are what the Astrobee shall provide to support the experiment. These are preliminary budgets and if Astrobee cannot support that, discussion with the payload provider can happen to reduce their expectations.

Subsystem	**Mass [kg]**
Payload - LiDAR	1.5
Payload - GPU	0.25
Payload - Capture system	2
TOTAL	**3.75**

Table 10.3: *Astrobee solution Payload Mass Budget*

Subsystem	**Mean Power [W]**	**Peak Power [W]**
Payload - LiDAR	30	60
Payload - GPU	40	60
Payload - Capture system	30	50
TOTAL	**100**	**170**

Table 10.4: *Astrobee solution Payload Power Budget*

In summary, the In-house solution provides full control and customization but requires greater development effort and system integration. The **Astrobee** solution offers a simpler, faster integration using an existing platform, but with less flexibility. Each approach presents a clear trade-off between autonomy and ease of implementation.

11 Subsystems preliminary design

11.1 Payload - LiDAR

The LiDAR will be provided by CSEM. It is based on the LiCoRIS project currently in development.

11.2 Payload - GPU

The pose estimation algorithm requires a lot of computing. Moreover, if we want to implement AI with Klepsydra, even more computing power will be necessary. Therefore, an embedded GPU is needed. Nvidia proposes such products, especially the Jetson Series, which are supported by ESA. They have various physical footprint, electrical power needs, and computing power, and more discussion with Klepsydra about their needs will be required to make an informed decision.

11.3 Payload - Capture system

The Capture system will be provided by ClearSpace. It is a scaled down version of the capture system of the ClearSpace-1 mission. It uses four arms with three articulations each.

11.4 Client object

The client object can be of various shapes (cube, spherical...) with possibly protrusions. It will be smaller and lighter than the spacecraft. To have redundancy in the ground truth system, in addition to the ArUco markers on its sides, it will have a small IMU inside it.

11.5 Propulsion

Note: this section is only valid for the in-house developed solution

The propulsion subsystem takes care of moving the spacecraft around. The Table 11.1 presents a summary of the main driving requirements for this subsystem.

ID	Title	Description
PROP.001	Purpose	The propulsion subsystem shall enable the spacecraft to move in space with 6 degrees of freedom (DOF)
SC.007	Spacecraft DoF	The spacecraft shall have 6 DoF.
SC.008	Spacecraft Linear Acceleration	The spacecraft maximum linear acceleration along each axis shall be at least 0.5 cm/s^2.
SC.009	Spacecraft Angular Acceleration	The spacecraft maximum angular acceleration around each axis shall be at least 0.3 deg/s^2.
ISS.028	Rotating Components	All rotating elements must be enclosed and remain below 200 mm in diameter and 8000 rpm in all conditions, unless safety-assessed.

Table 11.1: *Main requirements for the propulsion subsystem*

11.5.1 Technologies

Several technologies are possible to fulfill this function:

- **Fans:** utilizes rotating blades to generate thrust by moving air
- **Cold gas thrusters:** expels stored gas to produce thrust
- **Acoustic propulsion:** uses sound waves to induce movement

- **Wings flapping:** mimics the biomechanics of birds or insects, using oscillating wing motions to generate lift and thrust
- **Electric propulsion:** accelerate ions or plasma using electric and magnetic fields
- **Chemical propulsion:** involves chemical reactions that release heat, converting it into kinetic energy for thrust

The trade-off is made on seven criteria, listed below. Each possibility is then graded for each criterion with - in case of bad performance, 0 in case of neither bad nor good performance, and + in case of good performance. The sum is then made to decide the best solution, which is the one having the higher sum.

Criteria

- **Safety:** how safe for the astronauts and the station the solution is (higher is safer)
- **Thrust control:** how easy the thrust control is (higher is easier)
- **Noise and vibration:** how much noise and vibrations the system produces (higher is less noise and vibrations)
- **Mass and Volume:** how much mass and volume the system needs (higher is less mass and volume)
- **Power consumption:** how much power the system needs (higher is less power)
- **Maintenance:** how easy it is to maintain and repair in case of malfunction (higher is easier)
- **Technology Readiness Level (TRL):** how much the technology is ready for the flight, i.e. the maturity of the platform (higher is a higher TRL)

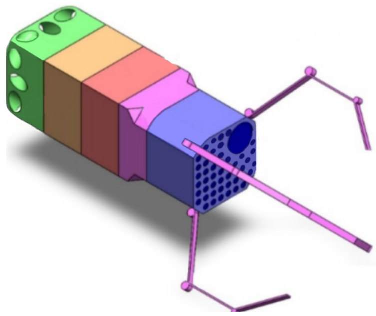
	Fans	**Cold gas thrusters**	**Acoustic**	**Wings**	**Electric**	**Chemical**
Safety	+	0	+	0	-	-
Thrust control	+	+	0	0	-	+
Noise and vibration	0	0	-	0	+	-
Mass and volume	+	-	0	-	0	0
Power consumption	0	+	0	0	-	+
Maintenance	+	+	-	-	0	0
TRL	+	+	-	0	+	+
TOTAL	**5**	**3**	**-2**	**-2**	**-1**	**1**

Table 11.2: *Trade-off Matrix Propulsion technology*

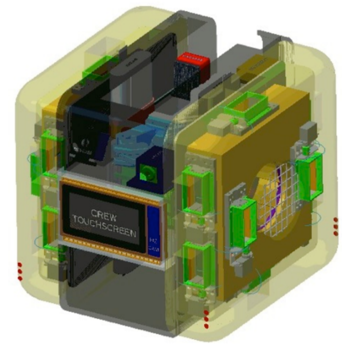
The technology chosen is fans, which has the best score.

11.5.2 Architecture using fans

Two architectures emerged. The first uses many small directed fans (Fig.11.1a, in the green section), whereas the second uses two big fans and valves to direct the flow (Fig.11.1b, fan is the circle in the middle of the right side and the valves are green).



(a) *Small directed fans*



(b) *Big fans and valves (©NASA)*

Figure 11.1: *Possible architectures*

The trade-off is made on six criteria, listed below. Each has a weight between 1 and 3, subjectively attributed, to highlight the more important criteria and not to have a criteria with minor importance be decisive in the choice. Each possibility is then graded for each criterion between 1 and 5 and the sum is made to decide the best solution, which is the one having the higher sum.

Criteria

- **Thrust control:** how easy the thrust control is (higher is easier)
- **Redundancy:** how much the system is resilient in case of failure (higher is more resilient)
- **Power consumption:** how much power the system needs (higher is less power)
- **Noise:** how much noise the system produces (higher is less noise)
- **Efficiency:** how efficient the system is (higher is more efficient)
- **Volume footprint:** how much volume the system needs (higher is less volume)

Criteria	**Weight**	**Small fans**	**Valves**
Thrust control	*3*	5	3
Redundancy	*2*	5	2
Power consumption	*1*	4	5
Noise	*1*	2	3
Efficiency	*2*	3	5
Volume footprint	*3*	4	1
TOTAL		**49**	**34**

Table 11.3: *Trade-off Matrix Small fans vs Valves*

The best solution is the small directed fans, especially for its low volume footprint and good thrust control.

11.5.3 Preliminary sizing

The final solution has 12 fans distributed on the cube, as shown in Fig.11.2. Four at the bottom {1, 3, 5, 7} and four at the top {9, 10, 11, 12} are pointing in the XY plan, and four other at the bottom are pointing in the Z direction (two on ZX {4, 8} and two on ZY {2, 6}). As reference, the capture system is at the top on the face where the fans {9, 10, 11, 12} are.

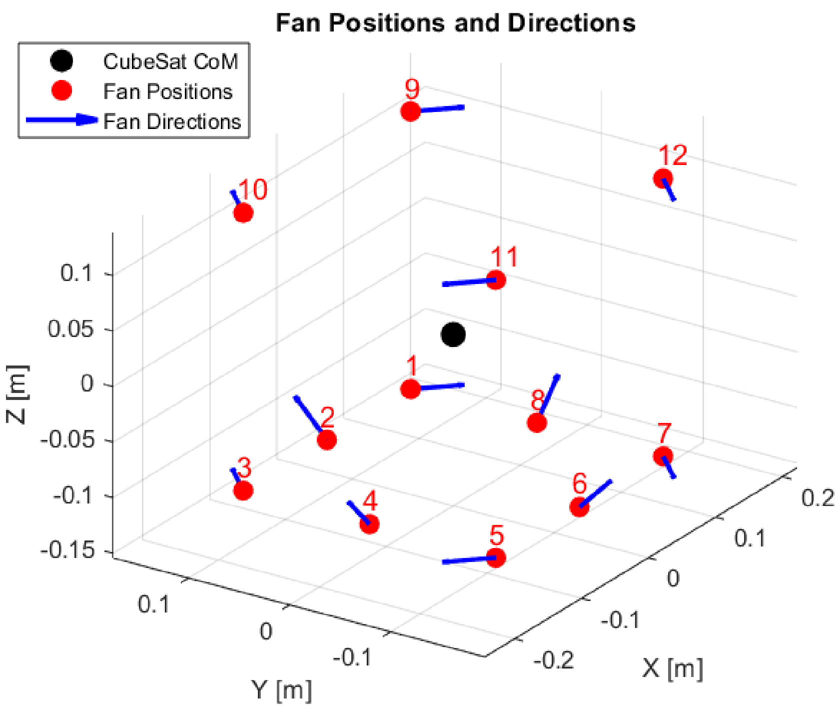


Figure 11.2: *Fans position and direction*

In addition to the requirements, some assumptions were made:

- The mass is exactly 10kg
- The fans are at the corner of the cube (exactly at 200mm)
- The center of mass (CoM) is at the center of the cube
- Only the forces of the fans are taken into account (no drag)

Table 11.4 presents the thrust required along each individual axis at maximum acceleration, as well as the maximum thrust for the most demanding combination of movements (this was estimated using the code in Annex C). All the values are for one fan, and when the thrust is different between the fans, the maximum was taken (as it is what will drive the choice).

Axis	**Max thrust [N]**
X, Y (linear)	0.010
Z (linear)	0.017
X, Y (rotation)	0.00044
Z (rotation)	0.00025
Max (combination of movements)	0.022

Table 11.4: *Thrust depending on the direction of movement*

As the fans are rotating parts at high speed, due to the conservation of angular momentum, they induce a rotation on the spacecraft. However, it can be canceled by slightly adapting the speed of the fans (having a component for the thrust and a component to counter the rotation). This takes only a few percent of the total force porduced by the fans.

11.5.4 Fan type

Two fan type are envisaged: electric ducted fan (EDF) and axial fan. The former has high thrust but also high rotating speed (several 10.000RPM), while the latter has lower thrust but lower rotating speed (<10.000RPM). Table 11.5 shows the thrust of both type in function of the fan diameter.

Diameter [mm]	20	30	40
EDF thrust [N]	~0.25	~1	~2
Axial fan thrust [N]	~0.06	~0.12	~0.25

Table 11.5: *Thrust in function of diameter*

Due to the ISS requirement on rotating speed and as a small 20mm axial fan still provides enough thrust, it has been decided to use this type and size.

11.5.5 Summary

The propulsion of the chaser is done using electric fans. Twelve air propellers are distributed around the spacecraft. The propellers are 20mm axial fans which provide around 60 mN of thrust, while the most demanding movement needs 22 mN.

11.6 Other subsystems

The other subsystems were not within the scope of this semester project. However, they must go through a preliminary study before the next phase of the PrOXISS project.

12 Recommendations

12.1 Propulsion

We recommend to use **Astrobee**, but it is only a recommendation as said before in Section 11.5, as other political unknowns have to be considered. If all stakeholders are *GO* for Astrobee (meaning SSO/ESA agree, payload providers agree, and if PrOXISS is accepted in the Astrobee program), it is recommended to use it as it reduces the complexity a lot and enables one to focus on the payloads. If, however, there is a *NOGO* from one stakeholder, everything can still be developed in house, but more resources will be required.

12.2 Ground truth

For post-processing and performance assessment of the relative navigation algorithms, ground truth tracking of both the chaser and client is essential. Initially, high-precision motion tracking systems such as OptiTrack were considered. However, after expert consultation and a review of the ISS infrastructure, it was confirmed that no OptiTrack system is currently available onboard the ISS, and deploying one would involve significant overhead in terms of mass (estimated at ∼20 kg), setup complexity, and calibration time, particularly within the constrained crew time available on the ISS.

To mitigate this, we recommend using the existing fixed cameras available in the Columbus module (typically at least three), combined with **ArUco visual markers** placed on the chaser and client objects, **instead of an OptiTrack system**. This approach offers several advantages:

- It requires no additional hardware deployment.
- It has a high TRL.
- It is widely supported in open-source vision libraries.
- It is simple to integrate and lightweight in terms of both computation and mass.
- It is already used in space rendezvous and proximity operations applications, e.g. by OrbitFab in their satellite servicing missions.

This recommendation was supported by the main stakeholders and is in accordance with their expectations.

12.3 Crew time - SSO Feedback

In the original SSO proposal, the crew time budget was 80 hours. In mid-may, SSO gave us a feedback on the original proposal, and said that the crewtime was too high. This budget was therefore reworked to have a more reasonable value. Three main action points were implemented:

- **All tests that do not need microgravity are done on the ground.** For example, the LiDAR and vision system can be mounted on the robotic arms in the dark room. The dark room facility enables realistic relative movements between vision system (chaser) and client, thus enabling the validation of the pipeline from LiDAR to RelNav algorithms. Another example is the mechanical capture system, which can be validated easily in a lab/facility such as ClearSpace's clean room.
- The experimental setup is simplified. For example, by **replacing the optitrack system with a camera setup and ArUco markers** that are already present on the ISS.
- The **experiment runs and VR experience are to be shortened**. The ConOps proposed in this document has been designed to minimize crewtime and even proposes optional steps, if the crewtime needs to be further reduced. The VR experience has been established as a secondary objective, due to viability and feasibility concerns.

The new budget is described in Table 12.1. The new total crew time is now 25 hours.

	Duration [h] (original)	Duration [h] (reworked)
Installation and Validation of the setup	12	3
Experiment runs	60 (15x4h)	20 (10x 2h)
VR Rehearsal and Visit	8	2
TOTAL	**80**	**25**

Table 12.1: *Crew time budget*

12.4 Need of the ISS - SSO Feedback

As emphasized by recent feedback from the SSO, it is essential to demonstrate the unique necessity and strategic value of conducting this experiment aboard the ISS. This section outlines both (1) the mission's specific need for the ISS and (2) the value offered to ESA, SSO, and the ISS through this collaboration.

1. Why is the ISS necessary for the PrOXISS mission?

The PrOXISS mission requires a prolonged and unconstrained microgravity environment to demonstrate autonomous rendezvous, approach, and capture of a free-floating, uncooperative client. No alternative testbed satisfies this requirement:

- **Parabolic flights** offer only 22-second intervals of microgravity, which is insufficient to validate full end-to-end guidance, navigation, and capture scenarios.
- **Air-bearing or frictionless platforms** are limited to 2D dynamics and cannot emulate the full 6 DoF behavior observed in orbital environments.
- **Ground-based testing** cannot reproduce the coupled dynamics and inertia effects of free-floating systems in microgravity.

The ISS offers a safe, controlled microgravity platform with sufficient volume, reliable power, high-bandwidth communication, and available crew assistance-making it the only viable platform for testing and validating these advanced space robotics technologies under realistic conditions.

Furthermore, for stakeholders such as ClearSpace, validating algorithms in a representative microgravity environment is a critical de-risking step in preparation for future operational missions (e.g., active debris removal, satellite servicing). The ISS also allows for repeated experiments, enabling iteration and refinement of capture strategies and autonomy frameworks.

2. Why is the experiment valuable to ESA, SSO, and the ISS platform?

From a strategic perspective, the PrOXISS mission aligns with Switzerland's and ESA's space priorities in the following ways:

- It directly contributes to European and Swiss goals in **space sustainability**, by advancing technologies in uncooperative rendezvous and capture, autonomy, and on-orbit servicing.
- It supports the development of **key Swiss niche capabilities**, including LiDAR-based sensing, computer vision, GNC algorithms for space applications, and mechanical capture systems, thus enhancing national competitiveness in the global IOS market.
- It showcases a **fully Swiss-built payload** or spacecraft flown on the ISS, which is a powerful symbol of national innovation and technical excellence.
- It promotes **public engagement** through high-visibility activities, contributing to ESA's and SSO's outreach and educational missions.

By leveraging the ISS, the PrOXISS mission not only validates critical space servicing technologies in a realistic environment but also provides strategic returns in capability development, sustainability, and public visibility for all participating institutions.

12.5 Other Recommendations

Recommendation	**Rationale / Description**
Use COTS components as much as possible.	Saves development time and effort; improves reliability and certification likelihood (e.g. COTS batteries).
Round edges or apply foam on free-floating equipment. Reduce free-floating equipment as much as possible.	Enhances safety for ISS crew and hardware; mitigates impact damage during free-floating operations.
Use existing control terminal present on the ISS, if possible.	Reduces total mass of the experiment.
Integrate IMU into client.	Enables measurement of true motion dynamics of the client in microgravity for ground-truth and validation.
Optional: Use existing objects on the ISS for additional client mock-ups.	Reduces total mass of the experiment.

Table 12.2: *Additional Recommendations*

After applying all these recommendations, the project will also reduce its originally proposed mass budget.

	Mass [kg] (original proposal)	**Mass [kg] (with recommendations)**
WIL chaser	10	10
Control terminal	6	2*
Client objects	4	3
Toolkit & Spare parts	10	10
Motion tracking System	20	0
TOTAL	**50**	**25**

Table 12.3: *Mass budget*

* Mass estimate refers to additional equipment required as control terminal in addition to one provided by the ISS.

12.6 Summary

- On-ground validation of payloads that do not necessarily need to be tested on the ISS (e.g., RelNav pipeline).
- Replace the OptiTrack system with a simpler computer vision-based ground-truth method (e.g., ArUco markers).
- Use Astrobee as an external propulsion system if permitted by stakeholders and program eligibility.
- Avoid sharp edges and minimize the number of free-floating modules unless absolutely required.
- Utilize equipment already present on the ISS where applicable (cameras, control terminal, additional mock-up clients, etc.).

- Use COTS components wherever possible to reduce development time and risk.
- Follow the high-level system requirements outlined in this document, including mass, size, and materials constraints (see Requirements A).
- Investigate additional mitigations to reduce major risks, such as crew time being too high (see Risk Analysis B).
- Clearly communicate the unique added value of conducting the experiment on the ISS, both in terms of what the ISS enables and what the experiment brings to ESA and the SSO.

The following table (Table 12.4 summarizes the impact of the proposed recommendations on the mission's overall mass and crewtime budget. It compares the budget estimates from the original proposal and the ones after applying the recommendations listed in this document. As shown in table 12.4, the total mass has been reduced by 2 and the total crew time has been reduced by a factor of 3.2.

	Original proposal	With recommendations
Crewtime [hours]	80	25
Mass [kg]	50	25

Table 12.4: *Budget Comparison*

Conclusion

Summary of Achievements

This project successfully achieved its primary objectives of defining high-level requirements, drafting a first version of the ConOps, and proposing a propulsion system architecture. This document also outlines areas of improvement in the original SSO submission and proposes recommendations, such as the use of Astrobee or the use of ArUco markers. Additional recommendations were presented and enable the reduction of mass budget by 2 and the crewtime budget by more than 3.

This was possible by first outlining the stakeholders expectations and main constraints. Requirements and ConOps were then derived from these expectations. Preliminary subsystems design and feasibility study, especially of the propulsion subsystem, were also made according to these requirements. Finally, other deliverables of phase 0 and A of a project as described in the ECSS standards were made, such as a high level risks analysis and timeline.

Future work

Several action points need to be taken in the short/medium term. First, contact the Astrobee team to organize a meeting to discuss the feasibility of PrOXISS on their platform. The preliminary design of the other subsystems shall be done. The ESA call for proposal must be answered shortly after its opening. Additionally, Interface Control Documents (ICDs) should be defined between major subsystems and external platforms (e.g., ISS, Astrobee, and the ground segment) to establish clear technical boundaries and responsibilities. A contingency strategy should also be established, identifying backup options and alternative mission paths (e.g. alternative microgravity platforms) in case the baseline plan encounters regulatory, technical, or scheduling obstacles. Finally, a cost study is important and needs to be done, as this point was not assessed in this report, but can be a driving constraint.

Lessons learned

Throughout the development of this preliminary study, several key lessons emerged. Engaging in discussions with real stakeholders early in the process proved essential for aligning expectations and validating assumptions. It also became apparent that the most limiting constraints are not always technical, but often political or administrative in nature. Due to these uncertainties, several assumptions had to be made and iteratively refined as the project progressed. Additionally, accessing accurate and detailed information regarding Parabolic Flights, ISS, ESA, and NASA requirements was particularly challenging, as much of the documentation is not publicly available or is difficult to navigate. These factors significantly influenced both the pace and scope of the study.

A Requirements

The complete set of requirements as of June 15th 2025 can be found below.

ID	Title	Description	Rationale	Parent
High Level Requirements				
MIS.001	Declaration of Purpose	The mission shall test techniques and strategies for capturing uncooperative objects in microgravity.	Mission purpose	
MIS.002	Testing in a Microgravity Environment	The experiment shall be conducted in microgravity to simulate space-like conditions for testing.	Ensures realistic and safe evaluation of on-orbit servicing technologies.	
MIS.003	Safe and Controlled Experimentation	The experiment shall be conducted in a manner that allows resets after failed operations.	Ensures risk-free testing and multiple trials for algorithm evaluation.	
MIS.004	Use of a Robotic Chaser Spacecraft	The experiment shall utilize a small robotic chaser spacecraft for proximity operations and client capture.	Essential for testing autonomous capture strategies in space.	
MIS.005	Use of a Tracking System	A tracking system shall be used to monitor the experiment's execution and collect performance data.	Provides precise tracking for performance evaluation.	
MIS.006	Multi-Scenario Testing Capability	The experiment shall allow for various clients shapes, sizes, and initial conditions.	Maximizes insights from a single mission by testing multiple scenarios.	
MIS.007	Public Outreach Consideration	The mission shall take into consideration public outreach and educational activities.	Ensures engagement with the public and promotes awareness of space operations.	
ISS				
ISS.001	ISS Compliance	The mission shall comply to all ISS, ESA and ground station reglementations and requirements.	The mission/experiment will be conducted inside the ISS.	MIS.002
ISS.002	Microgravity	The spacecraft and all its subsystems shall be able to operate under microgravity conditions (0g $\pm$ 0.2g (any direction)).	The mission/experiment will be conducted inside the ISS.	MIS.002

ID	Title	Description	Rationale	Parent
ISS.003	Volume available for experiment	The experiment shall be conducted inside a volume of 1.6*1.6*3 m^3.	Free volume of the Columbus Lab, which is the pressurised lab used for free-floating ESA experiments and technology demonstrations. The internal usable volume is around 1.8 * 1.8 * 3.2 m^3.	MIS.002
ISS.004	Transportation Volume	The volume of all the experiment equipment shall fit within the Cargo Transfer Bag size (to be defined later).	Ensures compatibility with Columbus stowage and safety margins.	MIS.002
ISS.005	Environmental Compatibility	The system shall operate within the Columbus module environmental range: 979–1027 hPa, 18.3–26.7°C, 25–75% relative humidity.	Ensures safe and continuous operation under ISS environmental conditions.	MIS.002
ISS.006	Power Supply Compatibility	If applicable, the spacecraft shall operate using available power lines: 28 V DC (10 A) or USB 2.0 (5 V, 500 mA).	Complies with Columbus electrical interface specifications.	MIS.002
ISS.007	Battery Safety	Only COTS pre-certified batteries shall be used.	Custom battery systems are discouraged unless explicitly approved by the ISS. Minimizes fire hazard and ensures compliance with ISS power safety requirements.	MIS.002
ISS.008	Battery Charging	Batteries may be charged onboard only if fully compliant with ESA/NASA procedures and safety protocols. Crew time is required for battery charging.	Reduces operational complexity and ensures astronaut safety.	MIS.002
ISS.009	Handling Safety	The spacecraft must be easy to retrieve and manipulate manually by an ISS crewman. Any free-floating equipment shall not have loose parts or sharp edges (safety against impacts e.g. foam on corners). There shall be no parts that get loose or break at any time.	Prevents injury to crewmen and facilitates microgravity handling scenarios. Moreover, parts that get detached from spacecraft do not fall into ground, which can be dangerous.	MIS.002
ISS.010	Surface Temperature Limits	All exposed surfaces of the spacecraft shall remain between 4°C and 45°C.	Prevents injury to crew and meets touch temperature constraints.	MIS.002

ID	Title	Description	Rationale	Parent
ISS.011	Status Indicators	Flashing lights must be avoided unless justified and approved. The spacecraft should have visible status lights.	Allows visually monitoring of the system state.	MIS.002
ISS.012	Communication Protocols	The spacecraft shall use secure IP-based communication (SFTP or SSH) over Ethernet LAN via MPCC.	Ensures compliance with ISS IT and electromagnetic compatibility rules.	MIS.002
ISS.013	Combustion Prohibition	The experiment shall not use or produce combustion under any conditions.	Combustion is strictly prohibited inside the ISS due to fire risk in enclosed oxygen-rich environments.	MIS.002
ISS.014	Material Flammability	Materials flammability shall be pass NASA flammability tests in accordance to Test 1 (Upward Flame Propagation) of NASA-STD-6001B Appendix A.2.4 or Test 1 (Upward Propagation Test Method) of ECSS-Q-70-21 or Test 4 of ECSS-Q-ST-70-21.	Reduces risk of onboard fire and supports safety certification.	MIS.002
ISS.015	Electrical Wiring	Electrical wire insulation shall be tested for flammability in accordance to NASA-STD-6001B Test 4 or ECSS-Q-ST-70-21 Test 3 (Electrical Wire Insulation Flammability Test Method).	Electrical wire insulation for arc tracking shall be evaluated by test or analysis with a method to be agreed by ESA.	MIS.002
ISS.016	Cooling	The experiment shall be air-cooled only, using cabin air; no water cooling shall be used.	No water cooling allowed. ISS flow-down requirements.	MIS.002
ISS.017	Ventilation	The experiment shall not obstruct cabin airflow and operate safely with ventilation velocity 0.051–0.203 m/s that occurs in the ISS.	ISS Flow-down requirement.	MIS.002
ISS.018	Material Off-Gassing	Materials shall meet the off-gassing limits specified in NASA-STD-6001B or ECSS-Q-ST-70-29.	Prevents long-term atmospheric contamination inside the ISS.	MIS.002

ID	Title	Description	Rationale	Parent
ISS.019	Forbidden Materials	Use of hazardous materials (beryllium, berrylium oxide, mercury, cadmium, lithium, magnesium, zinc, polyvinyl chloride (PVC), radioactive materials, polyamide insulated cables) is prohibited unless justified and approved.	Ensures toxicity, corrosion, and flammability limits are respected. Note: 'normal' Ethernet or USB cables are not allowed because they contain PVC or Polyamide. Also internal cables often fall into the 'forbidden' category and need to be replaced e.g. by LSZH (Low Smoke Zero Halogen) cables.	MIS.002
ISS.020	Cabling Material	Electrical cabling must avoid PVC or polyamide; LSZH cabling should be used.	v	MIS.002
ISS.023	Electromagnetic Safety	The spacecraft shall not emit high voltage, high current, or strong EM fields without ESA safety clearance.	Protects sensitive equipment and human operators.	MIS.002
ISS.024	Volatile Compounds	There shall be no use of prohibited volatile organics (e.g., methanol, acetone, ethylene glycol) unless fully contained and ESA-approved.	Avoids toxic accumulation in closed atmospheric loop.	MIS.002
ISS.025	Fluid Compability	All materials shall be evaluated by analysis for compatibility with applicable liquids or gasses. Materials exposed to corrosive or hazardous fluids shall be evaluated by analysis or tested for compatibility. Materials compatibility with liquid and gaseous oxygen shall be evaluated in accordance to NASASTD-6001B paragraph 6.3.	ISS Flow-down Requirement.	MIS.002
ISS.026	Structural Safety	A Structural Verification Plan and Fracture Control Plan shall be prepared and approved by ESA.	Ensures structural integrity and load path verification during storage, handling, and operation.	MIS.002
ISS.027	Fungus Resistance	For missions longer than 1 year, all exposed materials shall be fungus-resistant.	Prevents biological contamination during long-term stowage.	MIS.002
ISS.028	Rotating Components	All rotating elements must be enclosed and remain below 200 mm in diameter and 8000 rpm in all conditions, unless safety-assessed.	Avoids dynamic instability and mechanical hazard in free-floating environment.	MIS.002
ISS.029	Soldering and Circuit Boards	All printed circuit boards should use conformal coating.	Prevents the release of toxic components into the cabin air and provides additional mechanical fixation for the components.	MIS.002

ID	Title	Description	Rationale	Parent
ISS.030	Propulsion system	No chemical propulsion shall be used.	ISS Flow-down Safety Requirement.	MIS.002
ISS.031	Shatterable Material	Shatterable materials such as camera lenses shall be contained such that 50 micron or larger particles are not liberated in the cabin. Shatterable materials shall not be stressed (no delta pressure). Camera lenses shall be recessed, supervised by the crew when in use, and placed in protected storage or contained when not in use.	ISS Flow-down Safety Requirement.	MIS.002
ISS.032	Pressure Relief Systems	Pressure-relief systems must be testable or use passive safety devices(e.g., burst discs).	Avoids overpressure risks during ascent or operations. More detailed requirement: Payloads using relief valves shall be designed such as a periodic re-test of the valves is possible once the payload is on board ISS. Alternatively, the payload shall: • use overpressure protections that do not require periodic retest, such as a burst disc; • use relief valve with a threaded fitting and upstream pressure isolation that can easily be replaced; • provide overpressure protection that can be retested in-place; • provide overpressure protection that can be manually verified periodically in-place (relief valve with a manually opening device).	MIS.002
Parabolic Flight				
FLI.000	Documentation Compliance	The experiment team shall prepare and submit all required documentation as per NoveSpace and ESA guidelines.	Required to pass safety and integration reviews prior to acceptance into a flight campaign.	MIS.002

ID	Title	Description	Rationale	Parent
FLI.001	Microgravity	The spacecraft shall be able to maneuvre in a controlled way and shall be able to maintain stability in microgravity (0 g ± 0,02 g in Jx, ± 0,01g in Jy, ± 0,03 g in Jz).	The experiment will be conducted in microgravity onboard the parabolic flight.	MIS.002
FLI.002	Duration of one experiment run	Each experiment run shall not exceed 22 seconds of microgravity per parabola.	Each flight allows only 30 x 22s experiment windows.	MIS.002
FLI.003	Experiment Setup Timing	Except for this first experiment, the experiments reset/setup shall be completed within the time of level flight window between parabolas. (mostly 2 minutes, sometimes 5 or 8 minutes).	There are 2 minutes between each parabola. Between sets of 5 parabolas, there is more time of level flight (5 or 8 minutes).	MIS.002
FLI.004	Structural Integrity During 1.8g	The equipment shall withstand 1.8g for 20 seconds, repeated twice for each parabola.	Equipment is subject to stress during ascent/descent of each parabola.	MIS.002
FLI.005	Power source	If the system requires a power source, it shall be able to operate with a power source of 230V AC with a maximum power of 2–3.5 kW.	Available power onboard NoveSpace flight.	MIS.002
FLI.006	Dimensional Constraints of experiment runs	The experiment equipment shall be sized under 2*2*2.25 m^3 (length*width*height).	To fit within the main cabin volume (2*2*2.25 m^3). More space is available in length and width, but with less height. Moreover, the experiment proposal is more likely to be accepted on a NoveSpace Parabolic Flight if the surface area of the experiment is less than 2*2m^2.	MIS.002
FLI.007	Dimensional Constraints of equipment	The experiment equipment shall be loadable through a 1.80*1.07 m^2 door.	The experiments are loaded on the flight through a door that is 1.80 m high and 1.07 m wide.	MIS.002
FLI.008	Cabin Environment	The experiment shall operate within 825 ± 5 hPa pressure, 17–25°C temperature, and max. 15% humidity.	Ensures correct functioning in cabin atmospheric conditions.	MIS.002
FLI.009	Mass of Free-Floaters	Free-floating modules should have a mass <10 kg.	Flow-down requirements of NoveSpace (for safety).	MIS.002
FLI.010	Restraining of Free-Floaters	Free-floating modules should be restrained (e.g., cage, tether, netted area).	Flow-down requirements of NoveSpace (for safety).	MIS.002

ID	Title	Description	Rationale	Parent
FLI.011	Mass of equipment	Each equipment or payload assembly should have a mass <20kg.	Flow-down requirements of NoveSpace (for manual transportation, installation and operational reasons).	MIS.002
FLI.012	Safety Restrictions	The experiment shall not use combustion, radioactive materials, x-ray generators.	Flow-down requirements of NoveSpace (for safety).	MIS.002
FLI.013	Batteries	Free-floating equipment shall only use COTS certified Lithium batteries. All other equipment should avoid custom lithium battery assemblies and should use COTS.	Flow-down requirements of NoveSpace (for safety). Note: Non-COTS Lithium batteries for non-free floating equipment can be approved if necessary.	MIS.002
FLI.014	Number of Personnel	The experiment shall be prepared and operable by a maximum of two operators.	Two people (scientists / crewman / operators) are allowed per experiment.	MIS.002
FLI.015	Noise and Vibration Resistance	All spacecraft subsystems shall operate properly under the range of 70-88 dB noise and associated vibrations.	The aircraft undergoes noise during parabolic flight (70-75 dBA during weightlessness, 80-88 dBA during hypergravity phases).	MIS.002
FLI.016	Laser and Electromagnetic Restrictions	The experiment shall not use laser class 4 or extreme magnetic fields. The experiment should not use laser class $\geq$1M.	Flow-down requirements of NoveSpace. The magnetic fields must not interfere with other payloads.	MIS.002
FLI.017	Chemical and Liquid Handling	Liquid volume should remain below 0.5L, double sealed, and no flammable, toxic, or explosive substances allowed.	Minimizes risks related to spillage and volatile materials.	MIS.002
FLI.018	High-Energy Systems	The experiment should not include high-energy mechanisms (e.g., centrifuges, springs, flywheels) unless explicitly approved.	Flow-down requirements of NoveSpace	MIS.002
FLI.019	Pressurised equipment	There should be no system with a pressure x volume (P.V) product above 4L.bar	Flow-down requirements of NoveSpac	MIS.002
FLI.020	Material temperature	The temperature of liquids shall be below 49°C, and shall be below 60°C for other equipment materials.	Flow-down requirements of NoveSpace	MIS.002
Tracking System				
MTS.001	Ground Truth	ISS Cameras: Ground truth video data shall be captured by cameras and downlinked post-experiment.	Supports validation of autonomy post-flight.	MIS.005

ID	Title	Description	Rationale	Parent
MTS.002	Marker System	Visual markers (such as ArUco markers) should be affixed to WILL and the target to support visual pose estimation.	Enables ground-based motion tracking using computer vision.	MIS.005
MTS.003	Data Sync	Time-stamped telemetry and camera frames shall be synchronized for offline error analysis.	Ensures proper data alignment for RelNav validation.	MIS.005
MTS.004	Client IMU	The client IMU shall integrate an IMU to provide additionnal positionning data.	Ensures redundancy in ground truth.	MIS.005
Spacecraft				
SC.001	Upgradeable Design	The spacecraft shall be designed to allow software modifications for future experiments.	Supports long-term research and technology evolution.	MIS.003
SC.002	Experiment Run Duration	Each experiment run duration shall not exceed 15 min.	Guarantees consistency in testing, optimizes crew time, and ensures repeatability of results.	MIS.003
SC.003	Number of Experiment Runs	The mission should conduct at least 30 experiment runs to ensure sufficient data collection and validation.	Maximizes learning opportunities, enables iterative improvements, and ensures robust testing of algorithms.	MIS.003
SC.004	Spacecraft Mass	The spacecraft mass shall not exceed 10 kg	Estimation from cubesat standard (1kg/dm3) + mass of arms	MIS.004
SC.005	Power consumption	The spacecraft power consumption should not exceed 200 W.	Limited power onboard.	MIS.004
SC.006	Body volume	The spacecraft body (without the capture system) shall fit in a 200*200*200 mm^3 cube.	Keep the volume reasonable to allow movement inside ISS.	MIS.004
SC.007	Spacecraft DoF	The spacecraft shall have 6 DoF.	ClearSpace's requirement	MIS.004
SC.008	Spacecraft Linear Acceleration	The spacecraft maximum linear acceleration along each axis shall be at least 0.5 cm/s^2.	Ensures the safety and stability of sensitive onboard equipment while minimizing the risk of collisions within the ISS.	MIS.004 ISS.004
SC.009	Spacecraft Angular Acceleration	The spacecraft maximum angular acceleration around each axis shall be at least 0.3 deg/s^2.	Prevents excessive rotational forces that could destabilize the spacecraft's orientation or cause damage to the ISS structure.	MIS.004
SC.010	Spacecraft Maximal Velocity	The spacecraft maximum velocity shall be at least 0.05 m/s.	Ensures that the spacecraft moves at a controlled speed, reducing the likelihood of impacts or interference with the ISS environment.	MIS.004
SC.012	Capture system	The spacecraft shall have a capture system to capture client object.	Mission goal, ClearSpace technology demonstration.	MIS.001 MIS.004

ID	Title	Description	Rationale	Parent
SC.013	LiDAR	The spacecraft shall have a Lidar to detect the client object.	Mission goal, CSEM technology demonstration.	MIS.001 MIS.004
SC.014	Navigation algorithm	The spacecraft shall support the implementation of real-time navigation algorithm.	Mission goal, CVLab technology demonstration.	MIS.001 MIS.004
Payload				
PL.001	Capture system mass	The capture system mass shall not exceed 2 kg.	ClearSpace's requirement	SC.004
PL.002	Capture system power	The capture system power consumption shall not exceed 50 W.	ClearSpace's requirement	SC.005
PL.003	Capture system size	The capture system shall fit in a hemisphere defined by base of 700*700*100 mm^3 to 300*100*100 mm^3 at top.	ClearSpace's requirement	SC.006
PL.004	Client object size	The client object size shall be 100*100*100 [±20*20*20] mm^3.	ClearSpace's requirement	SC.012
PL.005	Client object mass	The client object mass shall not exceed 1/3 of the mass of the spacecraft.	ClearSpace's requirement	SC.012
PL.006	Client object relative velocity	The client object relative velocity from the spacecraft shall not exceed 0.05 m/s.	ClearSpace's requirement	SC.012
PL.007	Client object tumbling rate	The client object tumbling rate shall not exceed 5 deg/s.	ClearSpace's requirement	SC.012
PL.008	Client object shape	The client object shape shall be variable, i.e. it can be a sphere, a cube, and have optionnal removable protusions (antennas, baffle, array mockups).	ClearSpace's requirement	SC.012
PL.009	LiDAR range	The LiDAR shall be able to acquire 3D images up to a distance of 5 m.	CSEM's requirement	SC.013
PL.010	LiDAR accuracy	The LiDAR 3-sigma ranging accuracy shall be less than 0.01 m on the entire range.	CSEM's requirement	SC.013
PL.011	LiDAR update frequency	The LiDAR shall update the measurements at at least 5 Hz.	CSEM's requirement	SC.013
PL.012	LiDAR mass	The LiDAR mass shall not exceed 1.5 kg.	CSEM's requirement	SC.004
PL.013	LiDAR size	The LiDAR shall fit in a volume of 100*100*100 mm^3.	CSEM's requirement	SC.005

ID	Title	Description	Rationale	Parent
PL.014	LiDAR power	The LiDAR mean power consumption shall not exceed 30 W.	CSEM's requirement	SC.006
PL.015	LiDAR luminosity	The LiDAR shall be able to acquire 3D images in an environment where the luminosity is 108 lux and 600 lux.	ISS and Parabolic Flight environmental constraint	SC.013
PL.016	Computer Vision Algorithms and Navigation Algorithms	The onboard real navigation algorithm shall compute 6-DOF pose estimates in real time using LiDAR data.	Supports autonomous guidance of the spacecraft	SC.014
Propulsion				
PROP.001	Purpose	The propulsion subsystem shall enable the spacecraft to move in space with 6 degrees of freedom (DOF).	Necessary for the mission	SC.008

B Risk Analysis

The risk analysis table as of June 15th 2025 can be found on the next pages and was done on an excel sheet and exported as pdf. Each risk is characterized by its potential impact and likelihood, rated on a scale from 1 (low) to 5 (high). The overall risk value is computed as the product of these two factors: Risk = Impact * Likelihood. Mitigation strategies aim to reduce either the likelihood, the impact, or both, and a revised risk value is provided post-mitigation.

ID	Type	Risk Description	# Impact	# Likelihood	# Risk	Contingency / Mitigation Strategy / Recommendation	Impact after mitigation	# Likelihood after mitigation	Residual Risk after mitigation
R.001	Project Risks	Unclear or incomplete requirements. Poorly defined, incomplete, or overly rigid requirements can lead to misalignment, scope creep, or insufficient system performance.	5	4	20	All stakeholders should review requirements and agree on a set of requirements that are acceptable for all stakeholders. Setup an agile review of requirements when important aspects of the mission changes.	3	1	3
R.002	Project Risks	Mismatch between project ambition and feasibility. Risk that the scope is either beyond realistic execution or too limited to justify ISS value.	4	3	12	Conduct a thorough Phase 0/A feasibility study early on to validate scope against resources. Regularly consult ESA and SSO for feedback on ISS justification and scope appropriateness. Use a progressive mission plan (e.g. break down into demonstrable steps like PF → ISS). Maintain traceability between objectives and technical capabilities.	3	1	3
R.003	Project Risks	Unrealistic Timeline or Delayed Milestones. Poor planning (e.g. underestimated time required for MAIT) or unforeseen delays disrupt schedule, jeopardize milestones.	4	4	16	All stakeholder should review the proposed timeline and agree on one timeline. The timeline should be detailed with the main milestones. All stakeholders should be aware of what are the deliverables for each milestone. The timeline should be reviewed and updated regularly if necessary. Moreovoer, build in a margin in the timeline to reduce impact.	3	2	6
R.004	Project Risks	Proposal not accepted.	5	4	20	Get in touch with SSO and ESA experts and insure an early interaction with them, communicate openly and get regular feedback on proposals. Reduce crewtime and highlight the ISS value for this project. Consult ISS, ESA and other standards and requirements early in the project. Draft a back-up plan, e.g. testing on another space station.	4	2	8
R.005	Project Risks	Delays in obtaining approvals or unexpected rescheduling from ESA and other mission authorities.	4	3	12	Engage ESA/SSO and CADMOS early for timing expectations. Submit documentation and experiment descriptions well in advance. Maintain a buffer in the timeline for administrative processes. Have alternate testing milestones (e.g., parabolic flight fallback).	3	1	3
R.006	Project Risks	Misalignment, miscommunication and poor coordination with stakeholders, whether it is regarding timelines, budgets, bottlenecks, task repartition (e.g. who is the responsible stakeholder for the Remote Control of spacecraft from the Earth?), etc. This can lead to misdesigns, diverging priorities & expectations among stakeholders, stakeholder conflicts, etc.	5	3	15	Organize bi-weekly sync meetings with all stakeholders. Use a shared platform (e.g., Notion, Confluence) for tracking decisions and timelines. Draft stakeholder expectations, needs, goals and objectives early on (in a feasibility study) and get a agreed and validated set of expectations tha is acceptable for all stakeholders. Develop a Responsibility Assignment Matrix to clarify task ownership. Define and freeze interfaces and handovers early.	3	1	3
R.007	Project Risks	eSpace being a coordination bottleneck or project loses momentum.	3	2	6	Assign dedicated project management personnel within eSpace. Delegate certain work packages or coordination roles to stakeholders. Set up automatic reporting systems for progress tracking. Implement a review structure with milestone gates and external accountability.	2	1	2
R.008	Project Risks	One of the main stakeholders quits the project.	5	1	5	Identify critical dependencies and seek backup partners or subcontractors. Use Memorandums of Understanding that outline responsibilities and continuity plans. Share technical knowledge across teams to avoid single-point expertise failure.	4	1	4
R.009	Project Risks	Poor outreach impact. This may reduce the visibility of the stakeholders and potential funding for future missions.	3	2	6	Add value and an educational edge to the outreach. Provide Galactic Studios with regular updates about the mission and provide all the necessary equipment. Add and update requirements regarding public outreach in the technical requirements, especially if the public outreach requirements induce some technical requirements.	2	1	2
R.010	Project Risks	Underestimated lead time for hardware procurement.	4	3	12	choose reliable, fast and known suppliers. Implement ease of manufacturing into design choices. Try to use pre-certified components and COTS as much as possible.	3	1	3
R.011	Financial & Resources	Resource shortages, mismanagement, or misallocation. Resources include funding, skilled personnel, equipment, materials, access test facilities, etc.	4	3	12	Add "cost" as a driving design metric. Account for budget margins in all kinds of resources. Be sure to plan ahead and get access to the required test facilities. Write out back-up plans & strategies in case there are resource shortages.	2	1	2
R.012	Financial & Resources	Overrun of financial budget. Unexpected increases in material costs, labor expenses, or unforeseen issues can lead to budget exceedances.	4	4	16	Account for budget margins. Write out back-up plans & strategies in case there are budget exceedances. Add "cost" as a driving design metric.	3	3	9

R.013	Financial & Resources	Crew time availability: ISS may allocate less crewtime than requested to this project.	5	4	20	Reevaluate and reduce crewtime. For example, by changing the conops, prevalidating technologies on-ground, replacing time consuming setup technologies by less consuming setups, etc. Put priorities on the experiments that are to be executed on the ISS.	4	2	8
R.014	Legal Risks	Data protection issues (e.g. public outreach with onboard video).	3	2	6	eSpace shall ask SSO and all other authorities and shall act as a legal consultant and coordinator on data protection issues.	2	1	2
R.015	Legal Risks	Political complications or legal risks (contracts, liability, governmental authority, etc.).	4	2	8	eSpace shall be in open communication with all mission authorities (SSO, ESA, NASA, etc.) and shall act as a legal consultant and coordinator on political issues.	4	1	4
R.016	Legal Risks	Regulatory Changes. New laws or regulations can impact project requirements and increase compliance costs.	1	3	3	Stay updated on regulatory changes that may occur in the near future.	1	2	2
R.017	Safety Risks	Not adhering with PF or ISS Safety requirements.	5	4	20	Get an safety expert for the PF and an ESA ISS payload safety engineer, as early in the project as possible, that acts as adviser throughout all steps of the design and MAIT.	5	2	10
R.018	Safety Risks	Damage to ISS during payload experiments.	5	3	15	Strictly comply with ISS Safety Requirements and PrOXISS requirements. Perform extensive pre-flight safety and risk analysis and adhere to the verification plan. Have fail-safes or abort mechanisms on active systems (e.g., capture arms).	5	1	5
R.019	Safety Risks	Damage to payload during transportation.	5	2	10	Have back-up components for the components that are most likely to break. Eventually prepare reparation equipment and a reparation manual for crewmen that are on-site (astronauts, parabolic flight crewmen, etc.). [Other mitigations and requirements TBD later in coordination with ESA, ISS and other mission authorities].	4	1	4
R.020	Safety Risks	Damage to payload during experiments.	5	3	15	Set up and validate a solid verification plan. Perform end-to-end rehearsals before integration. Include health-check sensors and auto-stop features. Have back-up components for the components that are most likely to break. Eventually prepare reparation equipment and a reparation manual for crewmen.	3	1	3
R.021	Safety Risks	Mechanical failure during capture (fragmentation or deformation of client, or capture system, etc.).	4	3	12	C.f. Verification plan	4	1	4
R.022	Technical & Operational	Requirements are not met.	5	3	15	Maintain requirements traceability matrix. Use verification and validation checkpoints at each milestone. Assign owners to each requirement. Include formal reviews (SRR, PDR, CDR) to validate requirement compliance.	4	1	4
R.023	Technical & Operational	Subsystem Failure (LiDAR, capture system, propulsion, etc.).	4	3	12	Implement de-risking exercices in the conops. Conduct hardware-in-the-loop testing before integration. Use COTS components with flight heritage where possible. Include Built-In Test Equipment and logging to detect early failures. Define critical components redundancy policy.	4	1	4
R.024	Technical & Operational	Interface incompatibility or integration impossible between payload and PF, ISS, Astrobee, or something else.	5	4	20	Review interface documents (e.g. SSP 57000). Include interface emulation in FlatSat or mock setups. Collaborate with platform providers during early phases (Get a PF expert / ISS payload specialist / Astrobee engineer). Develop interface control documents early.	4	1	4
R.025	Technical & Operational	Subsystems not interfacing with each other.	5	3	15	Perform integration testing well before final deployment. Use standardized protocols and physical connectors. Maintain shared interface documentation. ConOps should enable testing of some subsystems, even some other subsystems fail (e.g. closing to capture point can be done without LiDAR, as the capture system is planned to be done blindly).	4	1	4
R.026	Technical & Operational	Subsystem(s) is/are underperforming.	2	3	6	Define minimum performance thresholds for mission success. Run performance tests under expected operational conditions. Include calibration and tuning options in design.	1	2	2
R.027	Technical & Operational	Remote software upgrade issues.	4	3	12	C.f. Verification plan (rollback functionality if corrupted update, fail-safe recoveries, etc.) and use the expertise and advise of the ground station (CADMOS).	4	1	4
R.028	Technical & Operational	Failure of live demonstration.	2	4	8	Pre-record key parts as fallback outreach. Schedule multiple demonstration windows or reruns. Run thorough pre-flight rehearsals and dry-runs in analog environments. Define backup scenarios in case of partial success.	1	2	2

R.029	Technical & Operational	Unexpected behaviour of client /spacecraft / payload in microgravity.	4	2	8	Pre-characterize client / spacecraft mass/inertia; reinforce rigid capture and stabilization control loop. Make sure to do accurate and precise measurements and account for anomalies (e.g. microgravity fluctuations). Implement de-risking exercices in the conops.	2	1	2
R.030	Technical & Operational	Equipment Malfunctions: Breakdowns of machinery or systems can cause delays and downtime.	3	2	6	Plan some margin into the timeline that allows for these kind of delays.	3	1	3
R.031	Technical & Operational	VR/Outreach content unusable due to poor video quality/sync.	4	3	12	Make VR a secondary objective. Have clear technical requirements regarding the things Galactic Studios needs (camera resolution, etc.) and be sure to properly delegate them to the right stakeholders. Use multiple video sources. pre-flight camera calibrations. sync with telemetry clocks.	3	1	3
R.032	Technical & Operational	Mechanical shock/vibration during transport or launch.	3	2	6	Vibration tests (c.f. verification plan)	3	1	3
R.033	Technical & Operational	Supplied material are defectives.	3	2	6	Use reliable material suppliers. Test materials and implement these tests into the verification plan.	3	1	3
R.034	Technical & Operational	Other more detailed technical risks [TBD].				Verification plan.			

C Propulsion sizing code

```
clc; clear; close all;

%% Define CubeSat Parameters
m = 10; % kg (mass of the Sat)
l = 0.2; % m (length)
Il = 1/6 * m * l^2;
I = Il*eye(3); % kg*m^2 (moment of inertia tensor)

%% Define Fans Positions (relative to the center of mass)
r = [ 0.125,  0.125, -0.125;  % Fan 1 positionned at +x +y -z
      0.00,  0.125, -0.125;   % Fan 2 positionned at  0 +y -z
     -0.125,  0.125, -0.125;  % Fan 3 positionned at -x +y -z
     -0.125,  0.00, -0.125;   % Fan 4 positionned at -x  0 -z
     -0.125, -0.125, -0.125;  % Fan 5 positionned at -x -y -z
      0.00, -0.125, -0.125;   % Fan 6 positionned at  0 -y -z
      0.125, -0.125, -0.125;  % Fan 7 positionned at +x -y -z
      0.125,  0.00, -0.125;   % Fan 8 positionned at +x  0 -z
      0.125,  0.125, 0.125;   % Fan 9 positionned at  0 -y +z
      -0.125,  0.125, 0.125;  % Fan 10 positionned at +x -y +z
      -0.125, -0.125, 0.125;  % Fan 11 positionned at +x -y +z
      0.125, -0.125, 0.125];  % Fan 12 positionned at +x  0 +z

%% Define Fans Orientations (unit direction vectors)
d = [  sqrt(2)/2,  -sqrt(2)/2,  0;  % Fan 1 points along +x-y
        0,  sqrt(2)/2,  sqrt(2)/2;  % Fan 2 points along +y+z
       sqrt(2)/2,   sqrt(2)/2,  0;  % Fan 3 points along +x+y
      -sqrt(2)/2,   0,  sqrt(2)/2;  % Fan 4 points along -x+z
      -sqrt(2)/2,   sqrt(2)/2,  0;  % Fan 5 points along -x+y
       0,  -sqrt(2)/2,  sqrt(2)/2;  % Fan 6 points along -y+z
      -sqrt(2)/2,  -sqrt(2)/2,  0;  % Fan 7 points along -x-y
       sqrt(2)/2,   0,  sqrt(2)/2;  % Fan 8 points along +x+z
       sqrt(2)/2,  -sqrt(2)/2,  0;  % Fan 9 points along +x-y
       sqrt(2)/2,   sqrt(2)/2,  0;  % Fan 10 points along +x+y
       -sqrt(2)/2,   sqrt(2)/2,  0; % Fan 11 points along -x+y
      -sqrt(2)/2,  -sqrt(2)/2,  0]; % Fan 12 points along -x-y

%% Define Fans Torque Contribution
I_fan = 1e-5; % Moment of inertia of a fan around its spinning axis(kg*m^2)
omega_fan = 6000*2*pi/60 * ones(12, 1); % rad/s, fan speeds (positive or negative)
reaction_torques = -I_fan * (omega_fan .* d);
total_reaction_torque = sum(reaction_torques, 1);

%% Define Desired Accelerations
a_des = [0.0005*9.81; 0.0002*9.81; 0.0001*9.81];    % Desired linear...
    % acceleration (m/s^2)
alpha_des = [0.3; 0.2; 0.1] *pi/180;                % Desired angular...
    % acceleration (rad/s^2)

%% Construct the Equations of Motion
num_fans = size(r, 1);
```

```
% Compute force contribution of each fan
F = d;  % Each fan's force is in its given direction

% Compute torque contribution (r x F)
T_matrix = cross(r, d, 2);  % Each row is the torque contribution of 1 fan
T_matrix = T_matrix+reaction_torques;

% Construct the system A * T = b
A = [F'; T_matrix'];
b = [m * a_des; I * alpha_des];

% Solve using least squares (pseudo-inverse solution)
T_values = pinv(A) * b;

%% Display Results
disp('Required Fan Thrusts (N) (positive = forward, negative = reverse):');
disp(T_values);

disp('Reaction torque on satellite due to fan spinning (Nm):');
fprintf('[%f, %f, %f] Nm\n', total_reaction_torque);

%% Plot CubeSat and Fan Orientations
figure; hold on; axis equal; grid on;
xlabel('X [m]'); ylabel('Y [m]'); zlabel('Z [m]');
title('Fan Positions and Directions');

% Plot CubeSat center
plot3(0, 0, 0, 'ko', 'MarkerSize', 10, 'MarkerFaceColor', 'k');

% Plot Fans as points and directions as lines
for i = 1:num_fans
    plot3(r(i,1), r(i,2), r(i,3), 'ro', 'MarkerSize', 8,...
        'MarkerFaceColor', 'r');
    quiver3(r(i,1), r(i,2), r(i,3), d(i,1)*0.05, d(i,2)*0.05,...
        d(i,3)*0.05, 'b', 'LineWidth', 2, 'MaxHeadSize', 0.5);
    text(r(i,1)+0.02, r(i,2)+0.02, r(i,3)+0.01, sprintf('%d', i),...
        'FontSize', 12, 'Color', 'r');
end

legend('CubeSat CoM', 'Fan Positions', 'Fan Directions');
hold off;

%% Max thrust finder
% Define the Range and Step for Accelerations
% Linear acceleration limits
a_min = [0; 0; 0];            % Minimum desired linear acceleration (m/s^2)
a_max = 0.0005*9.81*ones(1,3);% Maximum desired linear acceleration (m/s^2)
a_step = 0.1*a_max(1);        % Step for linear acceleration (m/s^2)

% Angular acceleration limits
alpha_min = [0; 0; 0];               % Minimum desired angular...
```

```
    % acceleration (rad/s^2)
alpha_max = [0.3; 0.3; 0.3] *pi/180; % Maximum desired angularacceleration (rad/s^2)
alpha_step = 0.1*alpha_max(1);       % Step for angular acceleration (rad/s^2)

%Search for Combination of Linear and Angular Acceleration
max_force = 0;

% Loop over linear accelerations
for ax = a_min(1):a_step:a_max(1)
    for ay = a_min(2):a_step:a_max(2)
        for az = a_min(3):a_step:a_max(3)
            a_des = [ax; ay; az];

            % Loop over angular accelerations
            for alpha_x = alpha_min(1):alpha_step:alpha_max(1)
                for alpha_y = alpha_min(2):alpha_step:alpha_max(2)
                    for alpha_z = alpha_min(3):alpha_step:alpha_max(3)
                        alpha_des = [alpha_x; alpha_y; alpha_z];

                        % Compute force contribution of each fan
                        F = d; % Each fan's force is in its given direction

                        % Compute torque contribution (r x F)
                        T_matrix = cross(r, d, 2);  % Each row is the...
                            % torque contribution of one fan

                        % Construct the system A * T = b
                        A = [F'; T_matrix'];
                        b = [m * a_des; I * alpha_des];

                        % Solve using least squares
                        T_values = pinv(A) * b;

                        % Find the maximum force on any fan
                        for i = 1:num_fans
                            if abs(T_values(i)) > max_force
                                max_force = abs(T_values(i));
                            end
                        end
                    end
                end
            end
        end
    end
end

% Display results
disp('Max Force on any fan:');
disp(max_force);
```

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