POLITECNICO DI TORINO

Master's Degree in Aerospace Engineering

Master's Degree Thesis

Design and Operational Planning of the ARCap Module: Concept of Operations for Autonomous RvD and OOS, Launcher Vibration Analysis and End Effector Design

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Table of Contents

List of Tables

List of Figures

Abstract

The exponentially increasing number of satellite and space debris in orbit has led to an ever-growing interest and focus on Rendezvous and Docking (RvD) and On-Orbit Servicing (OOS) missions. Development of technologies able to perform such operations reliably, allow to extend operational life of working satellites, remove defunct one to have a more sustainable and reusable space infrastructures.
Withing this context, this thesis focuses on the early development (Phase 0 and A) of the ARCap Module by Kurs Orbital, a plug and play solution to be mounted as payload on hosting platforms. The module provide guidance capabilities during the rendezvous maneuver through its sensor suite and enables target capture and on-orbit servicing via integrated robotic arms.
The work focused on identifying mission operations through the definition of a detailed Concept of Operations (CONOPS), performing an initial vibration analysis for launcher compatibility, and conducting a Launcher Adapter Ring (LAR) analysis to support the preliminary design of the robotic arms' end-effector.
As for the operations needed from the module a state of the art state-of-the-art review of current RvD and OOS missions, such as MEV-1 and MEV-2 and ELSA-d, provided a benchmark for defining mission requirements and identifying enabling technologies. These elements, combined with the ARCap mission objectives, led to the definition of all operations the module must perform from launch to decommissioning, with particular focus on the nomanil ones enabling Rendezvous and Docking (RvD) and On-Orbit Servicing (OOS).
A vibration analysis was performed comparing the Launch vibration enviroment of the most common used launcher orldwide to define the worst case scenario to be used as benchmark for defining structural requirements. In parallel, a Launcher Adapter Ring (LAR) analysis was conducted to define interface constraints. Various end-effector concepts were reviewed and compared, leading to a preliminary design with tailored actuation and contact surfaces to maximize adaptability and robustness.
This work establishes the baseline design for the ARCap module operations, vibration analysis and end effector design, serving as a foundation for subsequent phases of the project, which will focus on detailed development of the operations, validation of the requirements, and system integration.

Chapter 1

Introduction

The thesis work is part of the development of Kurs Orbital's ARCap module (Adaptable Module for Autonomous Rendezvous and Capture), whose mission is to perform Autonomous Rendezvous, Docking, and on-orbit servicing.
The ARCap Module is a complex instrument designed as a Suite of Sensors and Robotic Systems – to be embarked on a variety of satellite platforms and normally resulting in a Service Satellite (S/S). ARCap empowers the S/S with a certain number of On-Orbit Services (OOS), whose basic operations rely on a space Rendezvous and Docking (RvD) and, depending on the specific mission, it is followed by a set of OOS operations of different complexity.
The targets of these services can be both space debris and satellites, the latter being either in a nominal state or an emergency, considering that non-collaborative rendezvous is in any case expected.
The following specific On-Orbit Services (OOS) are considered:

- Satellite
  - Visual inspection from distance
  - Orbit boost/orbit change – life extension
  - De-orbiting
  - Rescue from impractical orbits
  - Repairing (*)
  - On-Orbit Assembly (OOA) (*)
  - Refurbishment (liquid fuel and/or oxidizer) (*)
- Space Debris
  - Active Debris Removal (ADR) = Space debris De-orbiting

(*)*Note*: ARCap will not perform these operations in their entirety but will provide support in their execution.
The work presented in this thesis focused on three aspects of the Module Develop-

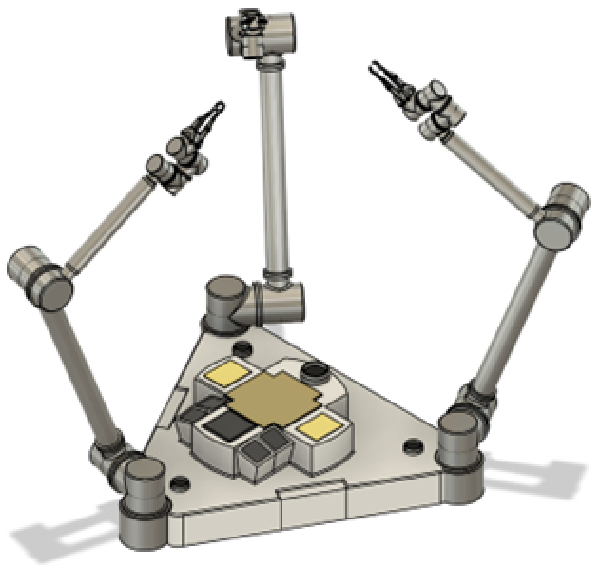


Figure 1.1: ARCap Module

ment, faced during the Phase 0 and the Phase A of the project:

- Define the CONOPS of the mission and identify Operational Risks
- Perform Vibration Analysis to determine the launch environment and define the derived requirements
- Analyze Launcher Adapter Rings' cross section to then Identify Preliminary End Effector Designs

CONOPS

The objective of this part of the work is to develop, starting from the mission objectives, the set of operations the module will need to perform throughout its lifetime. This is aimed at identifying the system-level functions required to achieve the mission goals.
This includes identifying the mission phases and the nominal operations necessary to fulfill the mission objectives, defining the system modes, and performing a risk assessment to highlight potential criticalities of the system.

Vibration analysis
The aim of this section is to compare the launch environments of the most commonly used launchers worldwide in order to define the Worst Case Scenario, and thus identify the most demanding conditions the system may face. This is done by superimposing the data from each launcher for each type of vibration (Sine, Acoustics, Random, Shock).
The results are then used to define the system requirements in terms of vibration, ensuring the module is designed to withstand the identified worst case scenario.

End Effector Preliminary Design
This section focuses on the analysis of Launcher Adapter Rings (LARs), which act as the interface between the satellite and the deployment mechanism, and serve as the grasping point for capture. The objective is to identify design commonalities across different launch vehicles by reviewing launcher user manuals and comparing the geometry of various adapter rings. The analysis revealed consistent features in their cross-sections, which was used for the preliminary design of robotic arm end effectors.

The structure of this thesis follows the development of the three aspects presented above, in the order in which they were introduced. At the beginning of each section, the necessary theoretical background is provided to contextualize and support the subsequent development.

1.1 The growing need for RvD and OOS Missions

The ability to perform Rendezvous, Docking and Servicing on satellites is becoming increasingly relevant as the number of satellites in orbit continue to rise. This consequently increases the need for technologies that enable maintenance, life extension, and debris removal. Traditional satellites were designed as isolated, single-use systems, to perform such operations, but recent advancements in RvD and OOS are reshaping this paradigm. From autonomous docking experiments to robotic servicing missions, space agencies and private companies alike are investing in technologies that will make space operations more sustainable and efficient.
In the following section of this chapter some of the most recent and notable RVD and OOS missions will be presented, highlighting key technological breakthroughs and challenges.
In the last decades the number of satellites has increased exponentially, according to the Index of Objects Launched into Outer Space maintained by the United Nations Office for Outer Space Affairs (UNOOSA), in just a year and a half, from January 2022 to June 2023, this number increased by 37.94% reaching 11,330 individual

satellites orbiting the Earth. To illustrate the rapid growth, consider that in five years, from 2018 to 2023, there have been more objects launched into space than in the previous sixty years of the space industry.[1]
This massive presence of satellites in orbit, and especially the rate at which this number is increasing is now bringing up new issues that will have to be addressed in the years to come. Most of the satellites are placed in Low Earth Orbits (LEO) (up to 2000km of altitude), enabling fast communication, high-resolution imaging, and real-time data transfer. This increasing density of active satellites and space debris in Earth's orbit, leading to a crowded environment, is often referred to as Orbital Congestion. This causes multiple issues:

- Radio Frequency Interference: more satellites require more communication frequencies, leading to interference and potential disruption of signals used for navigation, telecommunications, and scientific research
- Space Debris: more satellites mean a higher risk of collisions, which generate debris that can damage other satellites and spacecraft
- Risk to Manned Missions – space debris and uncontrolled satellites pose a threat to the International Space Station (ISS) and future crewed missions
- Environmental Impact: satellites that re-enter Earth's atmosphere can release harmful materials upon burning up, and the production and launch of satellites contribute to carbon emission
- Regulatory Challenges: the increasing number of satellites complicates international space laws and agreements, making it harder to manage space traffic and enforce debris mitigation policies

Up until now once the satellite reaches the end of it operative life, there are two options for its disposal:

- Burn Up in the atmosphere, either through a controlled re-entry or by natural decay, for satellites placed in LEO
- Moving to a Graveyard Orbit where it will stay indefinitely without interfering with active satellites

In order to reduce the need of launching satellites in orbit one way is to increase the operational lifetime by performing either servicing or life extension operations on them (OOS). Extending the life of a satellite also helps reducing Space Debris, a term referring to all non functional human-made objects orbiting the Earth. As presented in the previous chapter, in order to perform such operations it is necessary to first get close to the satellite to be serviced by performing Rendezvous

maneuvers and then rigidly connect to it (Docking). In the past this procedures were made either by controlling the servicer from ground or, for manned mission, from within the spacecraft. Lately, due to the increasing need to perform such operations and the advancement in technology, the effort is put into developing technologies capable of performing RvD in a completely autonomous way without the need to intervene from outside. Once docked, the servicer can perform Servicing and Life Extension Operation.
Decreasing the Orbit Congestion can be performed also by physically removing space debris, and thus using RvD technology to approach, grasp and get rid of it. Especially in those situations where a malfunction prevents the satellite from performing end-of-life operations properly, thus posing a danger to other satellites. Space debris removal can be achieved by either relocating it to a different orbit, away from congested regions, or by de-orbiting it and putting it into a decaying orbit.
All these aspects are extremely important for the future of space missions; therefore, extensive research and new technologies are continuously being developed.
As reference for this work the focus has been placed on missions that have already successfully performed operations in orbit either as a proper mission or as technology demonstration for future missions. For Autonomous Rendezvous and Docking as well as On-Orbit Services, two missions that are very important to consider as they represent the state of the art are:

- Northrop Grumman MEV-1 (2020)
- Northrop Grumman MEV-2 (2021)

As for space debris removal:

- Astroscale ELSA-d (2021)

1.2 State of the Art

1.2.1 Autonomous Rendezvous and Docking and On-Orbit Servicing Mission

As stated above, two groundbreaking missions for autonomous rendezvous, docking, and servicing are Northrop Grumman's MEV-1 and MEV-2.
Launched in 2020 and 2021, the MEV-1 and MEV-2 missions were the first to successfully perform commercial satellite life extension through autonomous docking. By employing mechanical capture systems, these missions extended the operational lifespan of geostationary satellites, demonstrating the potential of commercial satellite servicing. These efforts reflect the evolving capabilities of autonomous

systems in space, offering innovative solutions for maintaining and extending the lifespan of space infrastructure.

MEV-1 & MEV-2

As highlighted above one of the topics on which a lot of research and development is being made is life extension, which allows to increase operational life of serviced satellite, thus reducing the cost by avoiding the need of additional launches and space debris presence in orbit. MEV-1 and MEV-2 missions have been crucial for the development and the technology demonstration for performing such operations in orbit.

Mission	MEV-1	MEV-2
Developer	Northrop Grumman	Northrop Grumman
Launch Date	October 9, 2019	August 15, 2020
Launch Vehicle	Proton-M	Ariane 5
Launch Site	Baikonur Cosmodrome	Guiana Space Centre
Target Satellite	Intelsat 901 (IS-901)	Intelsat 10-02 (IS-10-02)
Initial Approach	Graveyard orbit docking	Direct GEO docking
Docking Date	February 25, 2020	April 12, 2021
Docking Method	Attached to liquid apogee engine	Attached to liquid apogee engine
Service Duration	5 years (extendable)	5 years (extendable)

Table 1.1: Comparison of MEV-1 and MEV-2 Missions

MEV-1 Mission Profile

Objectives of MEV-1 Missions were the following:

- ✓ demonstrate the first-ever docking with a GEO satellite (Intelsat 901)
- ✓ relocate the satellite from graveyard orbit back to operational orbit
- ✓ Take over station-keeping and attitude control for an additional 5 years
- ✓ prove the viability of commercial satellite servicing to extend mission lifetimes

MEV-1 was launched on October 9, 2019, from Baikonur Cosmodrome as dual payload with Eutelsat 5 West B. The latter was the first one separating from the upper stage, followed right after by MEV-1.
Once separated, it deployed Antennas, Solar Arrays and Electric Propulsion Thrusters. Over a 3 months period the satellite performed Rendezvous with the target (IS-901), the latter raised its GEO orbit to meet MEV-1 on a Graveyard one.

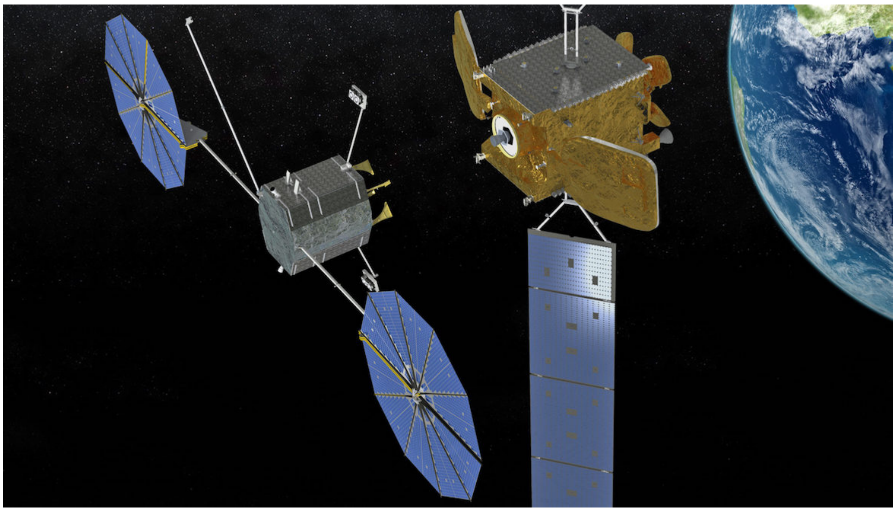


Figure 1.2: MEV-1 docking with Intelsat 901[2]

After an orbit matching phase the chaser circumnavigated and performed inspection from a distance of the target while preparing for final approach. The approach happened autonomously with the MEV-1 closing IS-901 from behind. After reaching the Near Hold point the chaser stopped and proceeded beyond only after receiving authorization from Ground.
The next stopping point was at about 1 m from the Target, from this distance the chaser performed autonomous docking by latching onto the inner rim of the target's Liquid Apogee Engine (LAE). Once docked tests have been performed to confirm combined Stack (Chaser+Target) Performance
MEV-1 reduced IS-901 Inclination to zero while relocating it on its new operational GEO Orbit at 27.5°west. Thus, completing the first part of the On-Orbit Service, the following one is to maintain the combined Stack's orbit for 5 years, after which MEV-1 relocated IS-901 to the GEO graveyard orbit, and after undocking, would move to the next client, the communications satellite Optus-D3, thereby extending its operational life after its launch in 2009.

MEV-2 Mission Profile

The MEV-2 mission built upon the success of MEV-1 with the following key objectives:

- ✓ perform direct docking in geostationary orbit (unlike MEV-1, which docked in a graveyard orbit first)
- ✓ take over propulsion and station-keeping for Intelsat 10-02

Mission Phase	**Status**
Launch and Orbit Raising	Completed
Rendezvous and Proximity Operations	Completed
Docking	Completed
Life Extension Service	Completed
Undocking	Completed
Future Redeployment	Planned

Table 1.2: MEV-1 Mission Phases and Completion Status

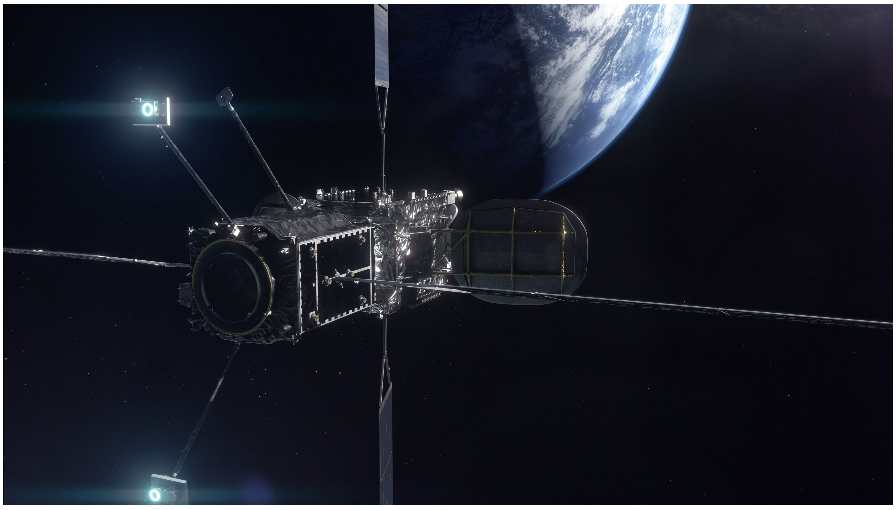


Figure 1.3: MEV-2 docked with Intelsat 10-02[3]

- ✓ provide life-extension services for at least 5 years
- ✓ validate improvements over MEV-1, making docking operations more efficient

MEV-2 launched on August 15, 2020, aboard an Ariane 5 ECA rocket from Kourou, French Guiana. After separation in a geostationary transfer orbit (GTO), the spacecraft used its onboard propulsion system to reach a circular geostationary orbit at approximately 35,786 km altitude above the equator. During this initial phase, MEV-2 also underwent system commissioning and health checks.

Upon reaching geostationary orbit, MEV-2 initiated a carefully controlled rendezvous with Intelsat 10-02, which was positioned at 0.8° East longitude. Using relative navigation sensors, including optical cameras and LIDAR, the spacecraft autonomously approached the target satellite, executing a series of maneuvers while strictly adhering to safety protocols to avoid collisions.

The docking phase took place on April 12, 2021, at a geostationary altitude of

approximately 35,786 km. This marked the first time a servicing spacecraft docked with a satellite that remained fully operational during the procedure. MEV-2 used a mechanical docking system to capture the satellite by its apogee engine nozzle, a standard feature of many GEO satellites,enabling the docking operation without requiring any pre-installed servicing hardware on the client satellite.
After docking, MEV-2 began providing life extension services. It assumed control of station-keeping and attitude stabilization for Intelsat 10-02, effectively extending the satellite's operational life by at least five years. This ensured the continuation of telecommunications services across Europe, the Middle East, and Africa, while postponing the need for an expensive replacement mission.
Finally, MEV-2 is designed for reuse. At the end of its current mission, it can undock and be reassigned to another satellite, making it a crucial element in the development of a long-term, sustainable satellite servicing infrastructure in geostationary orbit.

Mission Phase	**Status**
Launch and Orbit Raising	Completed
Rendezvous and Proximity Operations	Completed
Docking	Completed
Life Extension Service	Ongoing
Undocking	Planned
Future Redeployment	Planned

Table 1.3: MEV-2 Mission Phases and Completion Status

Key Technologies and Innovations
The MEV-1 and MEV-2 missions demonstrated a range of innovative capabilities in the field of on-orbit satellite servicing:

- **Standardized Mechanical Docking via Apogee Engine Nozzle**
  Both MEVs utilize a mechanical probe to dock with the apogee engine nozzle of client satellites—a feature common to many GEO spacecraft. This approach avoids the need for pre-installed docking hardware and enables servicing of satellites not originally designed for in-orbit maintenance

- **Autonomous Rendezvous and Proximity Operations in GEO**
  The spacecraft execute fully autonomous rendezvous and close approach maneuvers in geostationary orbit, using a combination of optical cameras, LiDAR, and onboard guidance algorithms. These technologies ensure precise, collision-free navigation during approach

- **Servicing Without Service Disruption**
  MEV-2 was the first servicing spacecraft to successfully dock with a satellite that remained active and fully operational during the entire procedure. This innovation proved that servicing can be done without disrupting commercial operations, enabling seamless life extension services for telecommunications providers

- **Reusable Servicing Platform**
  Both MEV spacecraft are designed for multiple missions. After completing a servicing operation, they can undock, maneuver, and rendezvous with a new client satellite. This reusability significantly reduces the cost and complexity of maintaining GEO satellite fleets

- **Full Attitude and Orbit Control Replacement**
  Once docked, MEV assumes complete control of the target satellite's attitude and orbit station-keeping. This effectively replaces failed or degraded systems onboard aging satellites, extending their service lives by several years

- **Safe and Passive Docking Strategy**
  The use of passive capture via the engine nozzle allows MEV to dock without requiring power, active control, or even functioning communication systems from the client satellite—ideal for servicing partially defunct assets

- **On-Orbit Demonstration of Commercial Servicing**
  MEV missions represent the first commercial, operational demonstration of GEO satellite servicing. They established the technical, operational, and regulatory precedent for future services, including refueling, repair, and debris removal

- **Ground Segment Integration for Servicing Operations**
  A dedicated ground infrastructure supports MEV operations with real-time telemetry, autonomous operation monitoring, and ground-in-the-loop control during key mission phases. This robust framework ensures mission reliability and responsiveness

1.2.2 Space Debris Removal

For Space Debris removal one of the most important missions is Astroscale's ELSA-d mission.
Launched in 2021, it marked a significant milestone in the development of space debris removal technologies. The mission demonstrated the capability of autonomous rendezvous and docking using a magnetic capture system to remove defunct satellites from orbit. This pioneering approach aims to reduce the growing risk of space

debris in LEO by actively removing objects that could pose a threat to operational satellites.
ELSA-d represents a leap forward in active debris removal, offering innovative solutions to ensure the long-term sustainability of space activities.

ELSA-d

Developer	Astroscale
Launch Date	March 22, 2021
Launch Vehicle	Soyuz
Launch Site	Baikonur Cosmodrome
Orbit	Low Earth Orbit (LEO), initial altitude of 550 km
Mission Duration	Approximately 6 months of active demonstrations

Table 1.4: ELSA-d Mission Specifications

Mission Profile
The ELSA-d mission aimed to demonstrate a series of autonomous servicing capabilities in orbit, including:

- ✓ Demonstrate autonomous rendezvous and docking in orbit using integrated hardware and software systems
- ✓ Perform target search and acquisition using absolute navigation, followed by handover to relative navigation
- ✓ Conduct fly-around inspections of the target satellite to enable visual assessment before docking
- ✓ Demonstrate docking with a cooperative target using a docking plate and magnetic capture system
- ✓ Validate magnetic capture technology for both non-tumbling and tumbling targets
- ✓ Test re-orbiting and controlled de-orbiting capabilities using onboard chemical propulsion
- ✓ Ensure mission safety with features like passive safety trajectories, collision avoidance, and abort procedures

✓ Operate a ground segment designed for in-orbit servicing, enabling operator-in-the-loop control and extended mission scenarios

The mission comprised both the Chaser, a minisatellite of around 180kg, developed by Astroscale and the Target, a microsatellite of around 20kg developed by Surrey Satellite Technology Ltd.(SSTL).

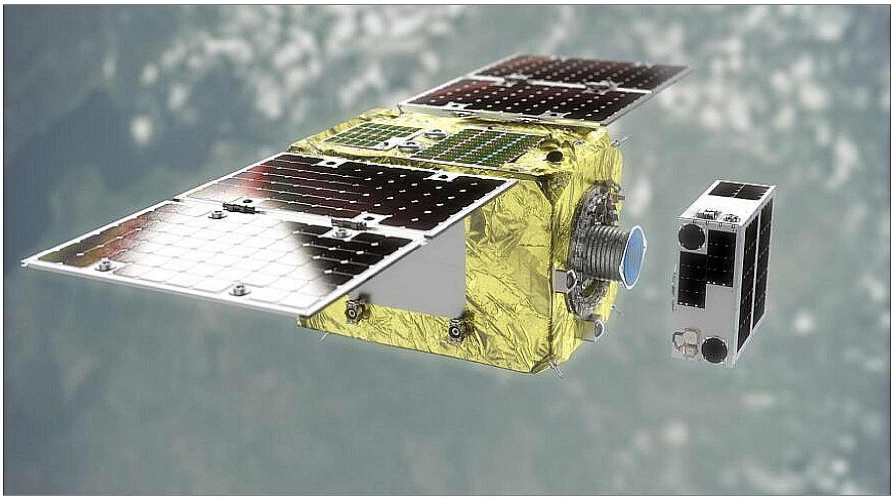


Figure 1.4: ELSA-d Chaser and Target [4]

The mission profile presented here corresponds to the CONOPS [4] of the mission, which divides into 7 successive phases, with increasingly complex demonstrations. Between them, when Chaser and Target are docked they enter a power and thermal safe routine phase.
In detail the Phases are the following:

1. **Launch and Early Orbit Phase (LEOP)**: Chaser and Target are launched together into the operational orbit of around 550 km

2. **Commissioning**: Chaser undergoes Commissioning ensuring subsystems are calibrated, and ready to start the demonstrations. The target is activated using the Target Activation Unit (TAU)

3. **Capture without Tumbling**: the Target Separation Mechanism (TSM) holds the chaser and target together during launch. After separation, the magnetic capture system is used to repeatedly capture and release the target, rendering the TSM unnecessary. After completing the Commissioning, started before, the chaser positions itself at set distances behind the target (holding points) to perform sensor calibration. Finally, the target is commanded to hold a set attitude, and the chaser goes in for the capture which is composed

of several sub-phases, including target acquisition and tracking, and velocity, position, and roll synchronization

4. **Capture with Tumbling**: this phase contains two demonstrations:

   - Inertial Navigation Validation Demonstration (INVD): to test the full rendezvous sensor suite
   - Diagnosis: fly-around performed to visually inspect the target by capturing images for subsequent download and inspection on the ground before capture:

   Once these two are completed the final capture is performed. On top of the sub-phases of phase 3 here images taken of the tumbling target are analyzed to determine its attitude. The Flight Dynamics System (FDS) then calculates and uploads a trajectory to align the chaser with the target, using settling for final alignment before capture

5. **Relative Navigation Demonstration**: this phase, aimed at testing target search capabilities, begins with the chaser thrusting away from the target until it loses sight of it. The chaser then moves into a safety ellipse to simulate an approach to an uncooperative target, as would occur in a full service mission. In ELSA-d, the Flight Dynamics System (FDS) is used, but the trajectory simulation is performed offline. In a full mission, the FDS would calculate the chaser's trajectory in real-time to guide it onto a rendezvous path with the target. The chaser comes within medium range of the target, eventually performing an absolute-to-relative navigation handover, switching to relative navigation technologies for the final approach and non-tumbling capture

6. **Re-orbit**: in the final phase, the chaser perform a re-orbit maneuver to reduce the target altitude, simulating final de-orbit in a full mission

7. **Passivation**: is performed at lower altitude and follows by a de-orbit burning up on re-entry. Mission maintains 25 year debris mitigation compliance, as the initial demonstration is only 550 km.

The expected duration of all phases, including the non-demonstration one (routine), was up to 6 months. As shown in Table 1.5 ELSA-d successfully completed the initial phases, including launch, commissioning, and manual capture demonstrations. While some autonomous operations were demonstrated, the full sequence of planned demonstrations, particularly autonomous tumbling capture, was not fully realized due to spacecraft anomalies.

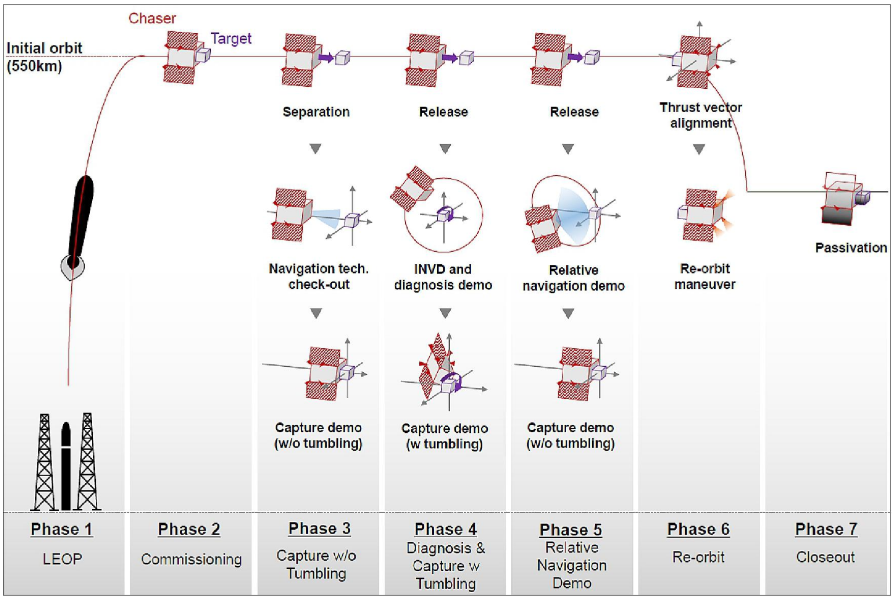


Figure 1.5: ELSA-d CONOPS [4]

Mission Phase	Status
Phase 1-2: Launch and Commissioning	Completed
Phase 3: Capture without Tumbling	Partially Completed
Phase 4: Capture with Tumbling	Incomplete
Phase 5: Relative Navigation Demonstration	Partially Completed
Phase 6-7: Re-orbit and Passivation	Completed

Table 1.5: ELSA-d Mission Phases and Completion Status

Key Technologies and Innovations

The ELSA-d mission showcases numerous innovative capabilities:

- **Autonomous Rendezvous and Docking**
  ELSA-d demonstrates an end-to-end solution for rendezvous and docking in space. It integrates advanced hardware and sophisticated software for guidance, navigation and control to manage both far-range and close-range approaches safely

- **Target Search Using Absolute Navigation**
  The system starts with absolute navigation using ground-based radar, optical tracking, and onboard GPS to find the target. Once located, the system switches to relative navigation for precision approach

- **Fly-Around Inspections**

Before docking, ELSA-d performs fly-around inspections of the target, allowing operators to visually assess the satellite. This is especially valuable if communication with the target is lost or disrupted.

- **Docking Plate for Semi-Cooperative Capture**
  ELSA-d uses a docking plate on the target, which offers a magnetic capture interface and a visually trackable surface for guidance. This setup creates a semi-cooperative scenario, simplifying the docking process compared to fully uncooperative targets.

- **Magnetic Capture Technology**
  The system employs magnetic capture technology, capable of securing both non-tumbling and tumbling targets. This solution avoids many complexities of tether-based or robotic systems.

- **Orbit Maneuvers and De-orbiting**
  After capture, ELSA-d can re-orbit to lower altitudes or perform controlled de-orbiting for end-of-life disposal. The spacecraft is also designed to perform passivation to prevent future debris generation.

- **Mission Safety Protocols**
  Mission safety is prioritized with passive and active abort strategies, safe trajectory maintenance, and constant ground segment oversight during critical mission phases

- **Dedicated Ground Segment for In-Orbit Servicing**
  The ground segment is tailored for in-orbit servicing, enabling operator-in-the-loop control during long operational windows. It allows for multiple ground station passes to ensure continuous mission support

The analysis of the missions outlined above is essential to understand the characteristics that a mission must have to ensure success, but more importantly, to identify the critical operations that must be carried out from an operational standpoint. It is crucial for properly framing the operational requirements of the ARCap mission and for defining its Concept of Operations (CONOPS), which outline the necessary procedures during rendezvous, docking, and subsequent on-orbit servicing (OOS) operations. These analyses not only provide a clear view of real mission technologies and processes, but are also key to optimizing the design of operations, ensuring efficiency and safety during execution.
The analysis of successful past missions provided valuable insights that contributed to shaping the ARCap mission architecture and its operational concept. While ARCap does not directly build upon a specific predecessor, understanding the strategies, challenges, and solutions adopted in previous rendezvous and capture

missions offered a solid foundation for defining its key requirements and high-level objectives. This chapter presents an overview of the ARCap mission, followed by a detailed description of its Concept of Operations (ConOps), highlighting the logic and rationale behind the proposed approach.

1.3 Comparison with State-of-the-Art Systems

omparing the missions presented above with ARCap, the following differences emerge:
ARCap improves upon existing state-of-the-art systems in several key aspects:

- **General-Purpose Capture Mechanism:** Unlike MEV, which depends on specific nozzle geometry, and ELSA-d, which requires a magnetic docking plate, ARCap employs a robotic arm with an adaptable end-effector, enabling it to capture a wider variety of targets, including unprepared objects.
- **Higher Level of Autonomy:** ARCap is designed for fully autonomous operations during rendezvous, inspection, and capture phases, surpassing the semi-autonomous or ground-controlled models of MEV and ELSA-d.
- **Expanded Mission Types:** While MEV focuses on life extension and ELSA-d on debris removal demonstration, ARCap supports a broader range of tasks such as inspection, repositioning, and potentially servicing.
- **Versatility and Modularity:** ARCap's modular end-effector and software-defined control architecture enable mission flexibility and potential reuse across different targets and mission profiles, unlike the single-target, mission-specific designs of MEV and ELSA-d.

Property	MEV-1 & MEV-2 (Northrop Grumman)	ELSA-d (Astroscale)	ARCap (Kurs Orbital)
Target Type	Cooperative GEO satellites	Cooperative & non-cooperative LEO targets	Potentially both GEO/LEO, cooperative and uncooperative
Docking Mechanism	Mechanical capture using liquid apogee engine (LAE) nozzle	Magnetic capture requiring docking plate	Robotic arm-based capture, adaptable to diverse targets
Guidance & Navigation	Predefined trajectories, limited autonomy	Vision-based navigation with some autonomy	Advanced autonomy with sensor fusion (vision, LiDAR)
Robotic Manipulation	None; rigid, non-adaptive docking	Limited manipulation; no robotic arm	Robotic arm with precision control and adaptability
Reusability / Modularity	One-to-one servicing, non-reusable after docking	Demonstration mission with partial reusability	Modular design supporting reusable deployment
Mission Profile	Life extension via permanent attachment	Debris capture and deorbit demonstration	Rendezvous, capture, repositioning, inspection, etc.
Autonomy Level	Low autonomy; ground-controlled	Semi-autonomous capture and proximity ops	Higher autonomy including real-time decision making
Compatibility with Unprepared Targets	No; needs compatible nozzle	No; requires prepared docking plate	Yes; capable of grasping unprepared or tumbling targets
Servicing Capabilities	Life extension (station-keeping)	Debris removal demonstration	Broader servicing: inspection, repositioning, refueling potential

Table 1.6: Comparison of ARCap with MEV-1, MEV-2, and ELSA-d

Chapter 2

ARCap Mission Overview and CONOPS

To frame the problem, it is important to understand that the design of a space mission requires a structured approach that ensures the mission is well-defined, feasible, and aligned with its objectives. The first thing to consider is the entire mission lifetime ranging from the initial concept (Mission Analysis) to end-of-life (Disposal).
Mission analysis consists of defining the mission objectives, assessing feasibility, and selecting an optimal approach. Once the mission concept is well-defined, the mission architecture can then be developed.
This chapter provides an overview of ow to approach the early phases of space mission design, and then focuses on the process of defining the mission CONOPS for the ARCap mission.

2.1 Mission Lifetime Cycle

The lifecycle of a space mission, considering the ESA standard presented in ECSS-M-ST-10C [5] is usually divided into 7 phases:

Phase 0	Mission analysis/needs identification
Phase A	Feasibility
Phase B	Preliminary Definition
Phase C	Detailed Definition
Phase D	Qualification and Production
Phase E	Utilization
Phase F	Disposal

Table 2.1: Mission Lifetime Phases

The initial phases (0, A & B) focus on defining the mission objectives and performing a mission analysis to define functional and technical requirements to develop the mission concept. Furthermore, during this phase activities and resources needed for space and ground segment development are identified. During these pre-development phases a technical and programmatic risk assessment is performed. Phases C & D focus on the development and qualification of both the space and ground segment and their respective systems while Phase E includes the activities related to the launch, commissioning, and utilization phase with the objective to maintain the orbital elements of the space segment and utilize and maintain the associated ground segment.
Finally, phase F includes all activities needed to safely dispose of the elements launched in space and eventually the ground segment.
Each phase is composed of multiple activities, whose results are then evaluated during project reviews conducted during and at the end of each phase. A positive outcome of the end-phase project reviews results in the progression of the project to the next phase. An overview of the project life cycle with reviews is shown below:

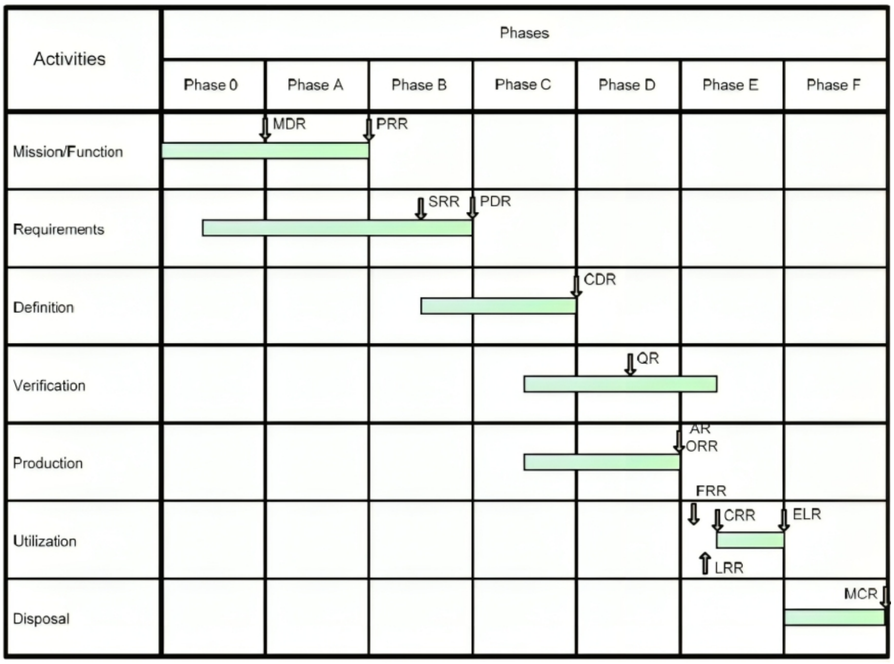


Figure 2.1: Lifecycle image from ECSS-M-ST-10C[5]

The activities of this study were part of the phase 0 and phase A development of the ARCap Module, therefore these two are presented in detail below.

Phase 0 - Mission Analysis/needs identification
The objective of this phase is to elaborate the mission statement, which highlights the mission goal and purpose, and thus the following aspects are covered:

- identify mission needs and expected performances
- define preliminary technical requirements specification
- identify mission operating constraints
- identify mission concepts
- perform preliminary risk assessment

The end of this phase corresponds to a positive outcome of the mission definition review (MDR). Subsequently the project moves to phase A.

Phase A - Feasibility
The focus of this phase is to perform a preliminary analysis of the mission's technical and financial viability by assessing different design options, system requirements, and possible risks. Tasks composing this phase are the following:

- Establish the Preliminary Management Plan (PMP), System Engineering Plan (SEP) and Product Assurance (PA) plan for the project
- Elaborate possible system and operations concepts and system architectures and compare these against the identified needs to determine levels of uncertainty and risks
- Establish the function tree
- Assess the technical and programmatic feasibility of the possible concepts by identifying constraints relating to implementation, cost, schedules, organization, operations, maintenance, production and disposal.
- Identify critical technologies and propose pre-development activities
- Quantify and characterize critical elements for technical and economic feasibility
- Propose the system and operations concept(s) and technical solutions, including model philosophy and verification approach, to be further elaborated during Phase B
- Elaborate the risk assessment

The end of this phase corresponds to a positive outcome of the Preliminary Requirements Review (PRR). Subsequently the project moves to phase B.

2.2 Mission Analysis

Mission Analysis represents the first step of the mission lifetime cycle (Phase 0). It is an iterative process that makes it possible to transform the mission objectives into specifications of the mission in terms of mission concepts, and eventually compare them, preliminary requirements and constraints. This phase can be developed and carried out, as presented in the book *"Space Mission Analysis and Design"* (SMAD) by J.R. Wertz and Wiley J. Larson [6], either as a **need-driven process**, where a mission is designed to fulfill specific objectives, or as a **capability-driven process**, where a new capability is identified, and a mission is developed to leverage it.

- Need-driven process →standard approach based on designing a mission to fulfill a specific set of mission objectives
- Capability-driven approach →based on identifying a new capability or a new way to use an existing capability and then finding a mission that could use such a capability

The main difference lies in the approach at the beginning of the project. In the first case, there is a customer or end user with a specific need, and the mission is designed to satisfy that need in the most efficient way possible. In the second case, a new or improved way to meet a need, whether more effectively, quickly, or at lower cost and risk, is identified, and the challenge becomes finding a customer with such a need who is willing to invest in the proposed solution. The ARCap framework represents a capability-driven approach in being built upon an already demonstrated capability, Rendezvous & Docking (RvD) and On Orbit Servicing (OOS), but with enhanced flexibility and versatility allowing it to operate in a wide range of mission scenarios. This is usually carried out trough successive step as shown in Figure 2.2.

The first step is to define the mission objectives, providing a high-level overview of its purpose and intended outcomes. From these, mission needs and requirements are derived to start framing the problem. This allows connecting the objectives with mission characteristics and specifications.

Once these high-level requirements are defined, they must be translated into alternative mission concepts and architectures.

The mission concept gives a high-level vision of the mission, including the overall mission goals, a basic strategy to achieve them, and a broad description of the systems and technologies involved.

The mission architecture is the detailed structure of how the mission will be executed. This includes the launch vehicle, spacecraft configuration, trajectory and orbital design, ground support and operations, and interfaces between modules.

To determine the best solution, different options are compared and evaluated. This is performed after determining the system drivers, which are the key factors or requirements that significantly influence the design, performance, and complexity of a system for each concept and architecture, further specifying and refining them. Once the evaluation is completed, one mission concept and architecture are selected, and specific system requirements are defined and allocated to the respective systems. These will drive the system design performed in the successive phases of the project. It is important to highlight that this is an iterative process(see the *Typical Flow* in the Figure 2.2) which allows continuous improvement of the proposed design to ensure it is as well-aligned as possible with the mission objectives and aligned with the identified drivers and requirements. This process ultimately leads to the optimal solution, which will then be developed and realized.

2.3 RvD and OOS

As it will be highlighted before the main objective of the ARCap module is to reach a target satellite (Rendezvous), connect to it (Docking) and then perform

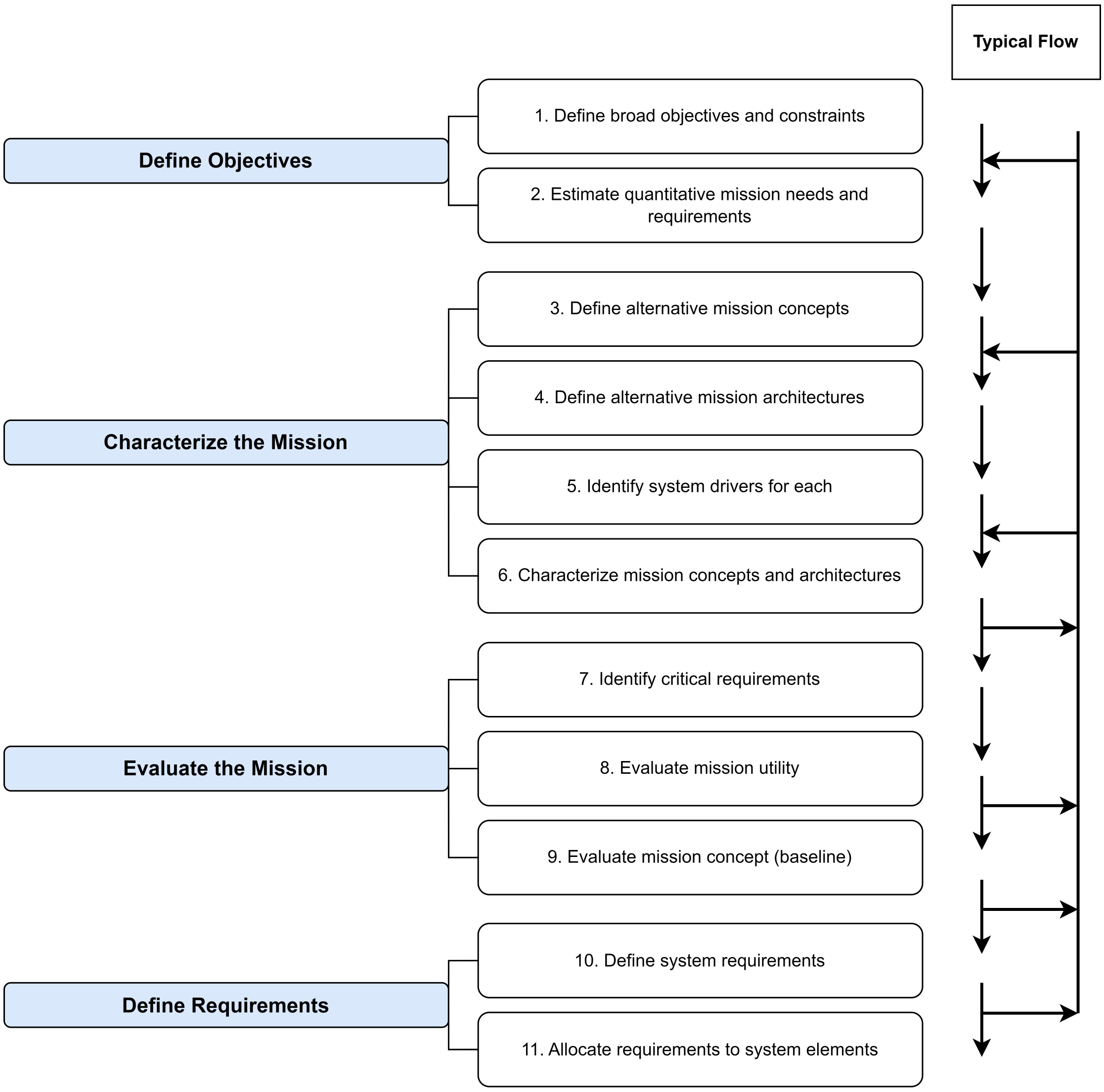


Figure 2.2: Mission Analysis process

operations on it (On Orbit Servicing). With reference to the ESA's Guidelines on Safe Close Proximity Operations guidelines [7] the following definition of such operations are given:

- Rendezvous: set of navigation-based maneuvers performed by two or more satellites in space to match their orbital parameters
- Docking: procedure that begins at the time of initial contact of the vehicles' mechanisms for capture and/or hard-mate and concludes when capture and/or hard-mating hooks/latches have been fully engaged.

Once the target has been reached via the rendezvous maneuver and a physical connection has been established at the end of the capture phase of docking, an orbiting system composed of the servicer and the target, referred to as the Stack, is achieved. Once these two phases are completed, OOS operations can commence. For OOS there's no widely agreed-upon definition, but, as reported in *"On-Orbit Servicing: Inspection, Repair, Refuel, Upgrade, and Assembly of Satellites in Space"* by J. P. Davis, J. P. Mayberry, and J. P. Penn [8], the term OOS refers to on-orbit activities carried out by a specially equipped space vehicle (the *servicer*), which performs up-close inspection of, or results in intentional and beneficial changes to, another spacecraft. These activities include: non-contact support, orbit modification (relocation) and maintenance, refueling and commodities replenishment, upgrade, repair, assembly, and debris mitigation. The wide variety of possible operations is mission-dependent and are also highly linked to both the Target and Servicer design and architecture. In fact, some of these operations (e.g. refueling, upgrade, assembly) can be performed only if both spacecraft involved are equipped for such operations, since specific interfaces are required for the transfer of consumables (refueling), data (upgrades), and structural modifications (upgrades & assembly). The set of operation considered as reference and from which the ARCap functionalities are selected is:

- Visual Inspection - procedure performed using optical sensors and/or cameras, aimed at assessing the target condition and supporting any subsequent operations. This can be performed also before the physical contact and connection (visual inspection from distance)

- Repairing/Maintenance - performing repairs and addressing wear and tear on the target to restore its functionality and thus ensuring its continued operation

- Upgrade - improving target's performance, capabilities, and overall mission effectiveness by installing advanced systems, enhancing software, or integrating new technologies

- Refurbishment/Mission Extension - replenish essential resources (propellant, coolants, and pressurants) consumed by the target during its mission to extend its operational lifespan.

- Support to space assembly - support the assembly and integration of large-scale systems in space

- Orbit boost / Orbit change - perform maneuvers while being docked to the target, to adjust its orbit by boosting it to a higher one, to extend its lifespan, or changing its trajectory, for mission reconfiguration or collision avoidance

- Rescue from impractical orbits - retrieve or reposition the target if in a non-functional or undesirable orbit, due to launch failure or orbital decay, restoring its operational orbits or moving it to a safer location
- De-Orbiting - safely remove defunct satellites or space debris by guiding them to burn up in Earth's atmosphere or moving them to designated graveyard orbits

2.4 Mission Architecture

As presented in the SMAD [6], *mission architecture* is defined as the collection of the eight major components: *Subject, Payload, Spacecraft Bus, Ground Segment, Mission Operations, Command Control and Communications Architecture, Orbit, Launch Segment* that define the technical and operational structure of the mission.

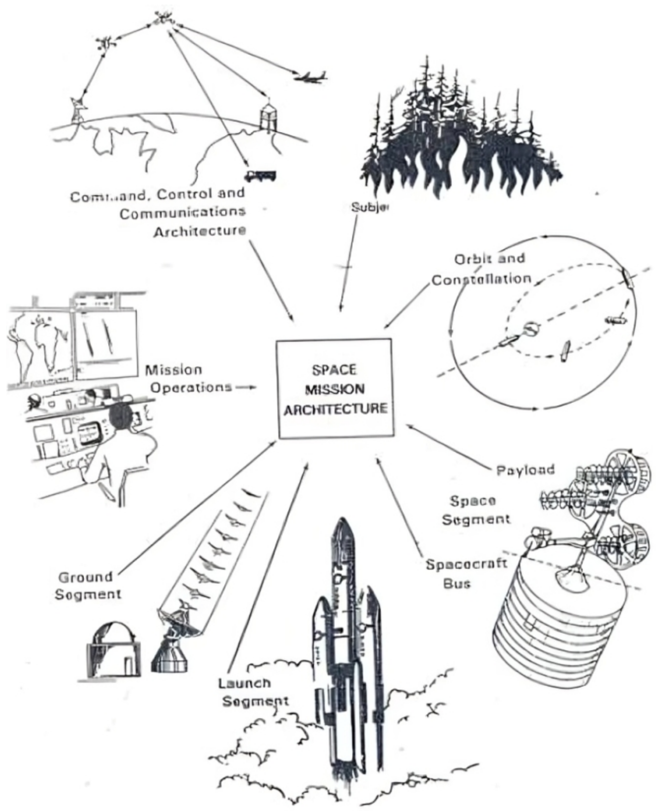


Figure 2.3: 8 elements of the mission architecture [6]

1. Subject

- passive: the element observed by the spacecraft
- active/controllable: the element with which the spacecraft interacts

2. Payload - spacecraft hardware and software that sense or interact with the subject

3. Spacecraft bus - group of subsystems that support the payload by providing orbit and attitude maintenance, power, command, telemetry and data handling, structure and rigidity and temperature control

4. Ground Segment - facilities and communications equipment associated with fixed and mobile ground stations around the world that enables the command and tracking of the spacecraft, receive and process telemetry and mission data and distribute the information to the operators and end user

5. Mission Operations - people, computers and software executing the mission operations concept and attendant policies, procedures and data flow

6. Command, Control and Communications (C3) Architecture - arrangement of components that satisfy the mission's communication, command and control requirements

7. Orbit - spacecraft path or trajectory in space

8. Launch Segment - the element that allows the spacecraft to get into orbit; it comprised the launch facility, launch vehicle, payload fairing and all associated ground support equipment and facilities

These 8 elements interact together as defined in the *mission concept* to meet the *end user* needs. The *end user* is defined as the entity that utilizes the data generated or transmitted by the spacecraft. Since the ARCap Module will be integrated on a satellite platform, representing one of its payloads, the focus of this study will be the development of this segment. Before diving into the analysis of the Module, it is important to understand how these elements are employed in a mission concerning Rendezvous and Docking (RvD) and On Orbit Servicing (OOS).

2.4.1 Key Aspects of a Mission Architecture for RvD and OOS

Considering a RvD and OOS mission, each of these 8 elements will perform specific operations in order to ensure the success of the mission. The operational role of each element is outlined below, highlighting the key characteristics and operational factors for both RvD and OOS.

Element	RvD	OOS
Subject	• Active subject is the target spacecraft • Chaser approaches for docking • Typically involves cooperative targets with built-in docking mechanisms	• Active subject is the spacecraft undergoing servicing • May involve non-cooperative targets • Requires additional capture mechanisms
Payload	• Sensors (LiDAR, cameras, Radar) for target tracking • Docking mechanisms: grappling arms, capture rings, docking ports • Redundant navigation and control systems • Soft capture mechanisms to absorb impact	• Robotic arms, refueling nozzles, cutting tools • Additive manufacturing units • Modular payload bays for mission adaptability • AI-driven fault detection systems • Tool changers and autonomous modules
Spacecraft Bus	• Provides power, attitude control, propulsion • Manages data for navigation and positioning • Redundant propulsion for last-minute maneuvers • High-precision RCS for fine control	• Enhanced support for servicing hardware • Advanced thermal control for long ops • Modular and expandable configurations • Extra fuel capacity for extended maneuvering

Element	RvD	OOS
Ground Segment	• Monitors trajectory and docking • Sends real-time commands • Predicts anomalies and takes action	• High data rate communications • Operator control of complex servicing • Advanced telemetry for health monitoring
Mission Operations	• Executes docking sequences • Defines approach zones and contingency plans • Redundant fail-safes	• Complex planning for tools and duration • Coordination among spacecraft and ground • Deals with unpredictable conditions
C3 Architecture	• Telemetry exchange between chaser and target • Ground or autonomous decision-making • Secure command links	• High-bandwidth feedback from robotic systems • Secure communication for coordination
Orbit	• Phasing maneuvers to align orbits • Considers perturbations and drag	• Rendezvous with non-cooperative targets • May need orbital repositioning post-servicing

Element	RvD	OOS
Launch Segment	• Launch parameters affect phasing efficiency and rendezvous maneuvers	• Multi-target servicing requires modular payloads • Extra fuel and onboard storage needed

Table 2.2: Mission Architecture for RvD and OOS

Given this overview of the key aspects to consider in relation to the eight elements of the mission architecture, combined with the mission analysis, it is now important to examine how all these elements converge and translate into successful on-orbit missions, as evidenced by missions carried out in recent years.

2.5 ARCap Mission Overview and CONOPS

As stated in the first chapter the ARCap Module is a complex instrument designed as a suite of sensors and robotics systems – to be embarked on a variety of satellites to empower the S/S with a certain number of On-Orbit Services (OOS). These operations are based on Rendezvous and Docking (RvD) and, depending on the mission, are followed by OOS tasks of varying complexity.
The following specific On-Orbit Services (OOS) are considered:

- Satellite
  - Visual inspection from distance
  - Orbit boost/orbit change – life extension
  - De-orbiting
  - Rescue from impractical orbits
  - Repairing (*)
  - On-Orbit Assembly (OOA) (*)
  - Refurbishment (liquid fuel and/or oxidizer) (*)
- Space Debris
  - Active Debris Removal (ADR) = Space debris De-orbiting

(*)*Note*: ARCap will not perform these operations in their entirety but will provide support in their execution.
The first part of the work focused on defining the CONOPS of the mission and identify operational risks.

CONOPS

As stated above, the ARCap module is designed to enable autonomous rendezvous and capture operations in space. Mounted on a host platform, it serves as a guidance and docking payload, using sensors and robotic arms to identify the target, provide guidance during the approach, and securely capture it. To effectively design the Module operations, it is necessary to consider the nominal operations which are performed during Rendezvous and Docking (RvD) and On-Orbit Servicing (OOS):

- **Proximity Operations** (considering [7] as reference)
  - **Client Phasing (CP)**: Phase starting outside of the Approach Zone (AZ) during which the orbital parameters of the client (Target Spacecraft, TS) and servicer (S/S) are brought closer, up to the border of the AZ
  - **Far Rendezvous (FR)**: First phase of the Close Proximity Rendezvous (CPR) where the servicer enters the AZ. The servicer must perform 3 DoF relative pose estimation and execute maneuvers to reach the border of the Keep Out Zone (KOZ)
  - **Close Rendezvous (CR)**: The KOZ is entered via the Approach Corridor. The servicer must perform 6 DoF relative estimation and control
  - **Capture (CAP)**: The servicer proceeds over the Point of No Return (PONR) to accomplish a stable stack through physical connection
  - **Separation (SEP)**: The servicer again proceeds over the PONR to accomplish a stable stack through physical connection
  - **Departure (DEP)**: The servicer's thrusters are activated to achieve an operationally safe trajectory to exit the KOZ via the departure corridor. This phase ends when the servicer is outside the AZ
- **On-Orbit Servicing (OOS)**: Performed with the captured target (listed in the previous page).

Each phase is defined by two decision points marking the beginning and end of the phase. It is important to highlight that during the decision-making process at these points, while awaiting its outcome, the S/S performs station keeping with respect to the Target.
This framework was used as the baseline to define the Module Nominal Operations and Mission Phases.

2.5.1 Mission Phases

Launch Preparation
After the integration of the Module on the PF, they are transported to the launch site for the final integration and testing in the payload fairing. All the tests and operations following the Module's integration into the Payload must be performed while considering the PF provider's specific needs and requirements.

Launch and Early Orbit Phase
During the Launch and Ascent phase, a satellite PF with an integrated ARCap Module, is located within the payload fairing. The module is OFF, and all its robotic arms are locked in stowed configuration. A survival thermal control system is required to maintain the internal temperature within survival limits. To avoid stress/fatigue to the iSSI interface, locking bolts shall be mounted at specific points along the structure perimeter.

Commissioning
Once the achievement of the correct orbit is confirmed the commissioning phase starts. The Module, that was Off until this moment, is powered on to begin commissioning phase by turning on its units and starts sensors calibration. During this phase the Module's units and their sensors are turned on and their functionality is checked. Objectives of this phase are:

- Verify Module systems functionality post-launch
- Perform initial calibrations of onboard instruments
- Test of teleoperation and visual servoing

Parking Orbit This orbit is the orbit in which the S/S could temporarily stay for one of the following reasons:

- Injection errors by Launcher or S/S, while planning corrections
- Temporary orbit between one mission and the next by S/S

In both cases, the ARCap Module should stay in either OFF Mode or Stand-by Mode and operate its sensors for either obstacle avoidance or TS search.

Nominal Operations During its operative lifetime the Module goes through the following successive phases:

1. Searching (SC): scanning the area to find the Target

2. Long-Range (LR) Tracking: tracking the position and movement of the Target

3. Target Identification (ID): identification of the Target

4. Short-Range (SR) Tracking: tracking of position, movement, and attitude of the identified target

5. Capture (CAP): capture of the Target

6. OOS

7. Separation (SEP): release of the target

8. Departure (DEP): departure from the Target

Further detailing of the Nominal Operations will be presented in the following section (section 2.5.1)

Parking Orbit/Preparation for the next mission Since the S/S could be performing more than one RvD and OOS Mission during its lifetime, once the current mission ends, the S/S can move to a parking orbit to get ready for the next one (if planned) otherwise the decommissioning phase can start.

Decommissioning Upon the completion of the S/S operational lifespan, the ARCap Module executes the final system checks, eventually transmits last data and shuts down non-essential subsystems to then proceeds with passivation.

Disposal Since the Module is attached to the PF, its disposal is carried out in accordance with the PF's end-of-life procedures.

Nominal Operations

2.5.2 Searching

Figure 2.4: Searching Mode

Scanning
The Module goes into *Searching Mode* to initiate detection of the Target. The Module sends a request to the Platform to adjust its attitude to point the module radar in the direction where the Target is expected to be located. During this phase the area is continuously scanned to detect the Target.

Confirmation of Target Acquisition
Once the Module has acquired the target via the Radar scan, a message is sent to the Platform confirming acquisition of the target.
Note: At this phase the target identity is not confirmed. What is confirmed here is the acquisition of what it is considered to be the Target (based on the data available to the module at that time).

2.5.3 LR Tracking

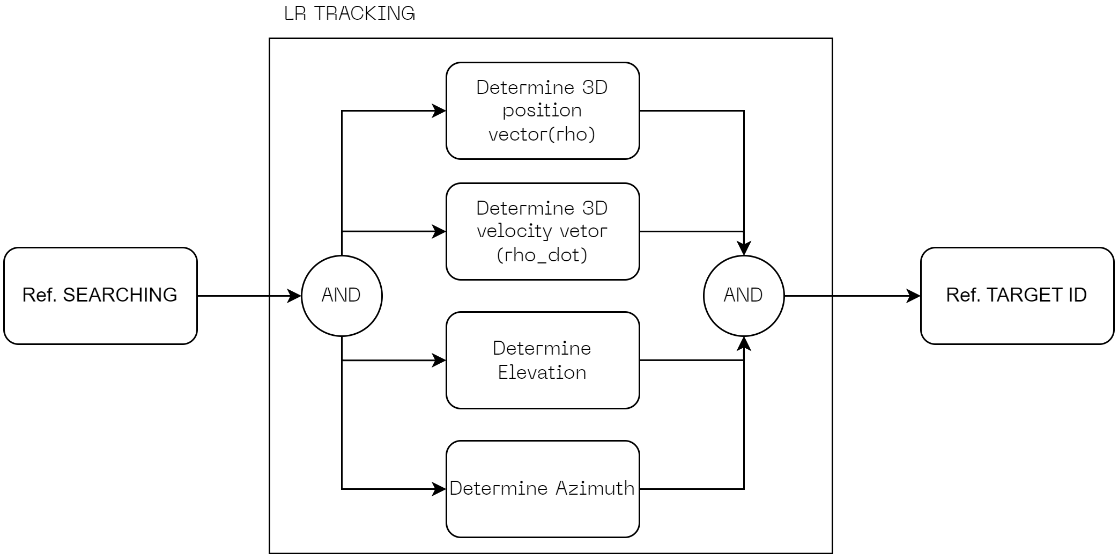


Figure 2.5: LR Tracking

After the correct acquisition of the Target, the module goes into *LR Tracking Mode*. This consists of continuously assessing, from the Radar data, the Target position (3D position vector, Azimuth and Elevation) and velocity (3D velocity vector) relative to the S/S.

2.5.4 Target ID

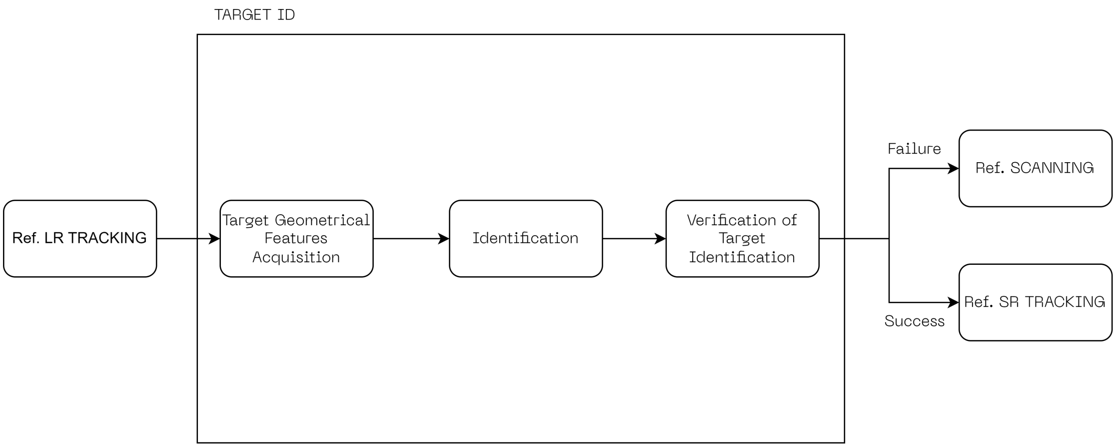


Figure 2.6: Target ID

Target Geometrical Features Acquisition
The Module acquires the Target Geometrical Feature to assess its three-dimensional characteristics (e.g. length,width,height and volume).

Identification
The Geometrical Features of the Target are compared with the data stored on board, to look for a match.

Verification of Target Identification
The comparison ends with the successful identification of the Target, thus the Module confirms that it has correctly acquired the observed target physical features.

2.5.5 SR Tracking

The Module shifts to *SR Tracking Mode* to continue tracking the Target, which is now confirmed to be the right one, and further acquire data with particular focus on the LAR, the designated interface for capture.

The tracking here is done by determining:

- Target distance (Range)
- Position (Azimuth and Elevation)
- Velocity (Range rate magnitude and 3D vector components)
- Attitude (Φ, θ, ψ)
- Attitude rate ($\dot{\phi}$, $\dot{\theta}$, $\dot{\psi}$)

LAR Position Determination
The Module identifies the LAR Position on the Target, assessing its position in the S/S reference frame.

Support to Approach Corridor Identification
The Module sends information such as the geometrical features and tracking data to support the identification—performed by the Platform—of the approach corridor. This is the spatial and dynamic envelope in which the S/S must remain during the Close Rendezvous in accordance with [7].

Tracking within the Approach Corridor
The Module tracks the position of the S/S within the approach corridor, to ensure to ensure it remains within the defined limits and thus guarantee the safe prosecution of the mission.

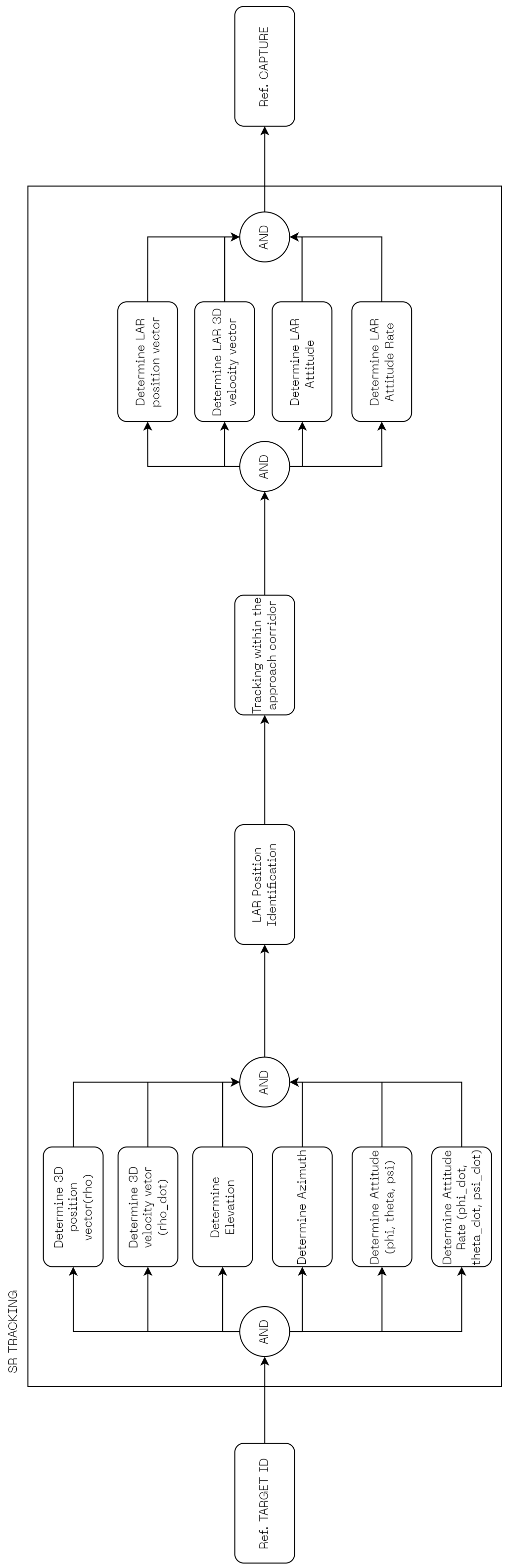


Figure 2.7: SR Tracking

LAR Tracking
Once a certain distance is reached, the Module starts tracking more precisely the LAR by determining its:

- Distance (Range)
- Velocity (Range rate magnitude and 3D vector components)
- Attitude (Φ, θ, ψ)
- Attitude rate ($\dot{\phi}$, $\dot{\theta}$, $\dot{\psi}$)

2.5.6 Capture

After the confirmation of the correct tracking of the LAR the Module goes into *Capture Mode* where, while keeping track of Target motion, performs the capture of the Target.
Note: All the operations below are performed while keeping the tracking of the Target active.

LAR Grasping Points Identification
The LAR tracking information is used to determine the points where the Capture with the Robotic Arms will be performed.

Confirmation of LAR Grasping Points Identification
The Module sends confirmation to the Platform of the correct acquisition of the points where the capture will occur.

Deployment of the Robotic Arm
The Robotic Arms used for capture are moved from the stowed position to the deployed position at a safety distance to avoid any collision with the Target.

Berthing Box Acquisition
The Module acquires the Berthing Box, i.e., the volume in space where the Target needs to be to correctly perform the capture.

Confirmation of Berthing Box Acquisition
The Module sends confirmation to the Platform that it has correctly acquired the Berthing Box.

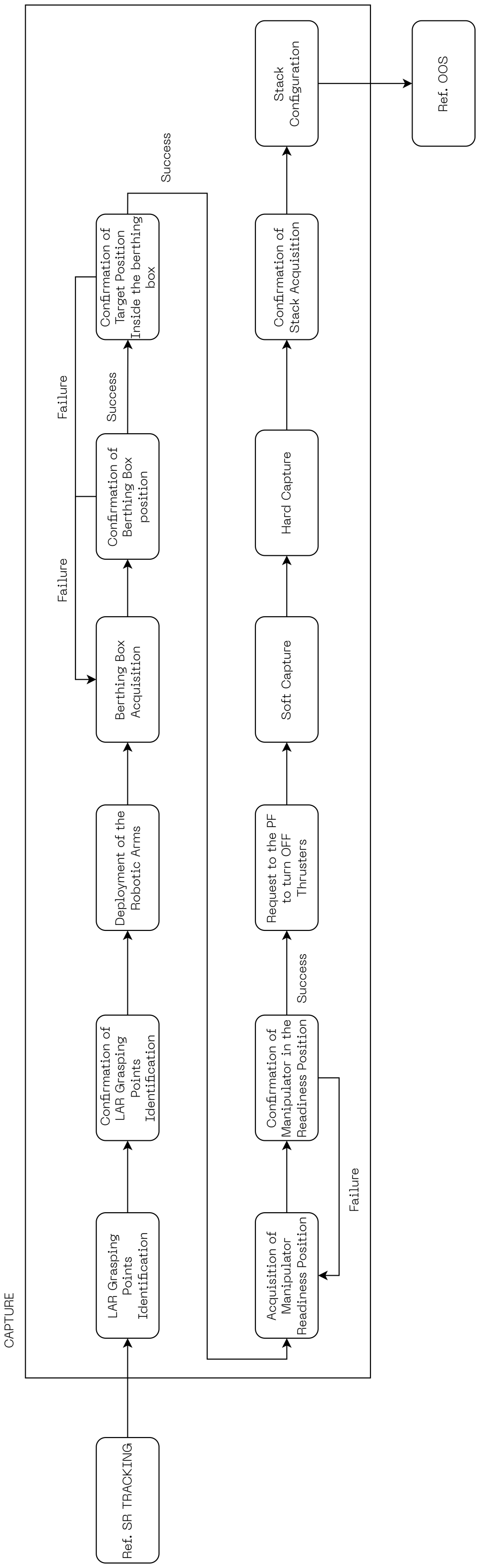


Figure 2.8: Capture

Confirmation of Target Position Inside the Berthing Box
Once the Berthing Box has been acquired, it is necessary to verify that the Target is correctly positioned within it. This is done by comparing the Target's position and orientation to the characteristics of the Berthing Box to ensure they match. When such a match is confirmed, it is communicated to the Platform.

Acquisition of Manipulator Readiness Position
After the Target is confirmed to be in the right position, it is necessary to move the Robotic Arm in a way to place the End Effectors/Manipulator in the correct position to perform the Capture.

Confirmation of Manipulator Readiness Position
Once the correct position is acquired, confirmation is sent to the Platform.

Request to the PF to turn OFF Thrusters
The Module sends a request to the Platform to turn OFF Thrusters in order to perform the Capture precisely without disturbances given by the propulsion.

Soft Capture
The End Effector, previously placed in the right spot, performs a soft capture of the LAR, by closing fast but with low contact force. This allows Target stabilization and prevents it from moving away.

Hard Capture
Once the target has been stabilized, hard capture is performed to firmly secure it by closing the End Effectors with high force but slow movement.

Confirmation of Stack Acquisition
The Capture concludes when the Stack (S/S + Target) acquisition is confirmed by the Module.

Stack Configuration
At this stage of the project, it is still unclear whether additional procedures will be required after stack acquisition.

2.5.7 OOS

As stated at the beginning of the chapter, the OOS operations considered are:

- **Satellite:**
  - Visual inspection from distance
  - Orbit boost / orbit change – life extension
  - De-orbiting
  - Rescue from impractical orbits
  - Repairing (*)
  - Space assembly (OOA) (*)
  - Refurbishment (liquid fuel and/or oxidizer) (*)
- **Space Debris:**
  - Active Debris Removal (ADR) = Space debris De-orbiting

(*)*Note*: ARCap will not perform these operations in their entirety but will provide support in their execution.

Visual Inspection from Distance
ARCap Module can perform an inspection of the TS, aimed at asserting its condition and integrity from a safe relative distance. This can be performed by directing the sensor toward the Target while the Platform executes fine controlled maneuvers to orbit around it, maintaining safety distance and appropriate relative positioning for continuous visual coverage.
During inspection, the status of the TS is used to detect visible anomalies, degradation, or damage to the target vehicle, such as:

- Detached components
- Surface erosion
- Thermal blanket damage
- Bent antennas
- Fluid leaks

This assessment can also support successive operations by detecting unanticipated configurations that could impact docking, servicing, or overall mission safety.

Orbit Boost / Orbit Change – Life Extension

The S/S can perform orbital maneuvers while docked to the TS through the ARCap module, which serves as the secure mechanical interface for coupling the two vehicles.

These orbit changes can be carried out in three non-exclusive ways:

- Boosting to a higher orbit to counteract natural orbital decay
- Altering orbital parameters for reconfiguration, optimization, or collision avoidance
- Remaining docked to the TS for the rest of its lifetime as a replacement for Propulsion and/or ADCS units

The S/S performs the entire maneuver, providing propulsion and attitude control, while the TS remains passive.

De-orbiting / Active Space Debris Removal

The S/S can perform orbital maneuvers while docked to the TS to remove defunct satellites or debris. These can be executed as:

- Controlled re-entry for burn-up in the atmosphere
- Relocation to a designated graveyard orbit

These actions are part of end-of-life procedures.

Rescue from Impractical Orbits

The S/S can retrieve a TS from an undesirable orbit caused by launch failure or orbital decay. Once docked, the S/S adjusts the TS's orbit using its own propulsion and attitude control systems.

Support to Repairing

The ARCap Module supports the S/S during repair operations aimed at restoring the TS's full functionality and extending mission life.

Support to Space Assembly

ARCap can support large-scale system integration in space by providing visual and operational assistance.

Support to Refurbishment
The ARCap Module supports the S/S while replenishing critical TS resources, such as:

- Propellant
- Coolants
- Pressurizers

2.5.8 Separation

At the conclusion of all OOS operations, the servicing spacecraft (S/S) separates from the Target satellite. The Module first transitions into the *Separation Mode.*
Note: All the following operations are performed while tracking the Target by determining its distance (Range), position (Azimuth and Elevation) and velocity (Range rate magnitude and 3D vector components), attitude (Φ, θ, ψ), and attitude rate ($\dot{\phi}, \dot{\theta}, \dot{\psi}$).

End Effector Opening
The separation process begins with the progressive release of the closing force on the LAR, thereby opening the end effector.

Release of the Target to Achieve a Certain Separation
To ensure a safe distancing and prevent any potential collision, the robotic arms apply a controlled force while releasing the Target.

Confirmation of Separation Distance Achievement
With the data from the Target tracking, it is confirmed that the desired separation distance has been achieved.

Retraction of the Robotic Arms
Once the right separation is achieved, the Module retracts its arms back to the stowed position.

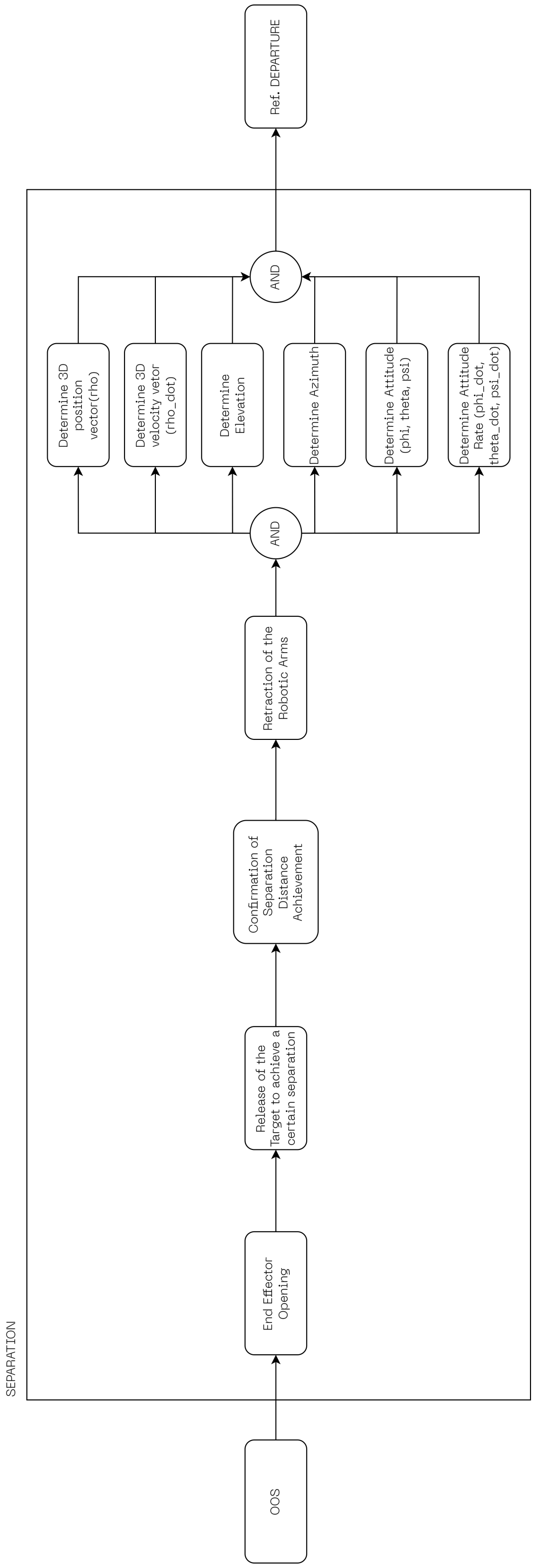


Figure 2.9: Separation

2.6 System Modes

The ARCap Module is considered as a Payload of the Platform, therefore its nominal operations will be performed in the "Payload Mode" of the PF. During launch, the Module is powered off. It activates during the Deployment and Commissioning Mode to perform its own commissioning procedures. In all other Platform modes, it remains in standby mode. As listed in sections above the Module has different modes it goes through during its operations. Such Modes and their relation are presented in Figure 2.10.

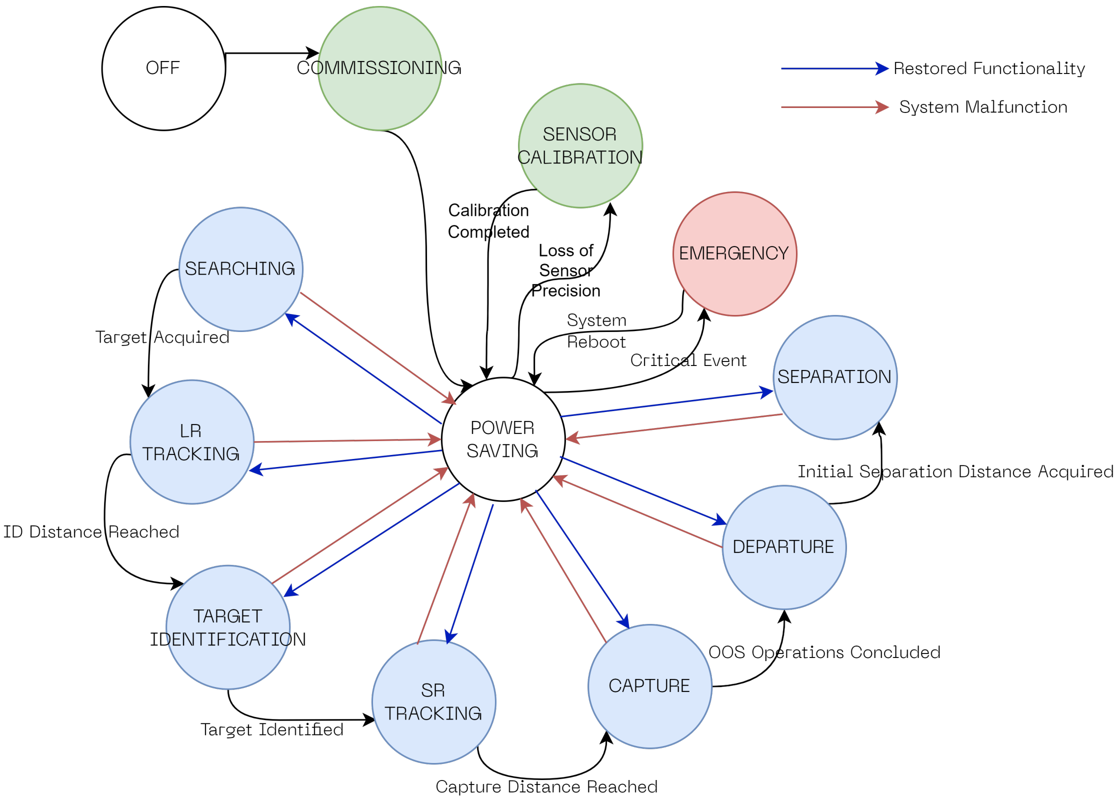


Figure 2.10: ARCap Mission Modes

2.7 System Requirements

Given the Mission Concept described above, and the operations of the module in the different phases, the following Mission and Module Requirements have been derived.

Requirement ID	Requirement Description
ARC-REQ-MS-SYS-0001	The ARCAP Module shall have a minimum operational lifetime of five (5) years in LEO.
ARC-REQ-MS-SYS-0002	The ARCAP Module shall be capable of operating in Low Earth Orbit, Medium Earth Orbit, and Geostationary Earth Orbit, as well as highly eccentric orbits such as Molniya and Tundra.
ARC-REQ-MS-SYS-0003	The ARCAP Module shall provide the Platform with the means for Rendezvous Operations with collaborative satellites, non-collaborative satellites and space debris.
ARC-REQ-MS-SYS-0004	The ARCAP Module shall provide the Platform with the means for Capture of collaborative satellites, non-collaborative satellites and space debris.
ARC-REQ-MS-SYS-0005	The ARCAP Module shall provide the Platform with the means for On-Orbit Servicing of collaborative satellites, non-collaborative satellites, and space debris.

Table 2.3: ARCap Module Requirements

2.8 Risk Assessment

Risks identified for the Module's Mission presented are, at this level, identifiable within three main areas:

- Technology Related Risks - the use of new technologies and new system configurations combined with the lack of flight heritage can result in uncertainties in performance, integration challenges, reliability concerns, and unforeseen failures

- Operational Risks/Contingency Scenarios - arising from unexpected anomalies or failures during mission execution

- Programmatic Risks - involve schedule delays, budget overruns, supply chain disruptions, and regulatory challenges that may impact on the overall feasibility and success of the mission

2.8.1 Technology Related Risks

The development of the ARCap Module, in its complexity, introduces a series of technology-related risks that must be carefully managed throughout the mission lifecycle. Given the module's role in performing autonomous rendezvous, capture, and servicing operations in diverse orbital environments, it must integrate highly reliable and sophisticated subsystems originally designed for terrestrial or controlled space applications. These adaptations, alongside the need for seamless integration and robust redundancy, highlight technological vulnerabilities that could compromise the mission.

- Adaptation of Terrestrial Technologies for Space Applications
- Integration Issues
- Reliability in Redundancy Systems

Adaptation of Terrestrial Technologies for Space Applications
Given the wide development of sensor technology in Radar, LiDAR, and machine vision, the idea is to leverage products and technologies from terrestrial applications and adapt them for space use.
However, this approach introduces several risks. These sensors have not been originally designed to withstand the harsh conditions of space, including extreme temperatures, vacuum, and radiation. Despite adaptation and qualification efforts, unforeseen reliability issues may arise due to material degradation, thermal expansion mismatches, or susceptibility to space radiation effects such as single-event upsets or total ionizing dose damage. Additionally, the adaptation process itself may introduce new failure modes if not rigorously validated. Thorough screening, careful selection, testing, and qualification are essential to mitigate these risks.

Integration Issues
The integration of sensors originally designed for terrestrial applications into a space system presents several challenges. Mechanical, electrical, and software interfaces must be carefully adapted to ensure compatibility with space-qualified components and architectures. Differences in power requirements, communication protocols, and thermal behavior can lead to unforeseen integration issues. Moreover, ensuring the reliable operation of these sensors within a spacecraft's constrained environment requires extensive testing to mitigate potential failures such as electromagnetic interference, structural mismatches, or thermal cycling. At the same time, integrating all components must ensure not only the desired performance of each subsystem but also the overall functionality and reliability of the entire system.

Reliability in Redundancy Systems
The reliability of redundancy systems is crucial in RvD missions, where any failure could put both the chaser and target spacecraft at risk. A collision could cause severe damage, potentially leading to mission failure for both. To prevent this, backup systems must be designed to handle potential hardware and software malfunctions. Redundancy can be implemented in two ways, depending on the criticality of the system:

- Hot Redundancy: the backup component operates simultaneously with the primary component. If the primary component fails, the backup takes over instantly without any delay. This is often used in critical systems where even a brief interruption is unacceptable. However, it consumes more power and may introduce additional complexity
- Cold Redundancy: the backup component remains off or in a low-power state until the primary component fails. Once a failure is detected, the backup system is activated. This approach reduces power consumption and wear on the backup but introduces a delay in switching to the redundant component. It is commonly used in space systems where power is limited, and immediate switching is not always necessary

Real-time fault detection, using Error Detection and Correction (EDAC) systems and recovery mechanisms are essential to maintaining control and ensuring safe operations.

2.8.2 Operational Risks and Contingency Scenarios

Considering the Mission Phases presented in Section 3.4, the risks encountered during each of them are analyzed, followed by the corresponding contingency scenarios that describe how to address such problems.

Applicable to all phases
The following problems can be encountered during all nominal phases indistinctly:

Category	Risks	Impact	Mitigation
Power System Malfunctions	Overvoltage or under-voltage damaging sensitive electronics	Permanent damage to components Loss of function	Use voltage regulators, surge protectors, and redundancy

Category	Risks	Impact	Mitigation
	Power consumption exceeding expected levels, leading to shutdown	System shutdown Inability to perform mission objectives	Implement power budgeting Dynamic power management Energy-efficient modes
	Power bus short circuit	Loss of power to critical systems Potential damage to circuits	Include overcurrent protection, redundant power paths
	Power cutoff/power transmission issues via the interface	Loss of data transmission Inability to operate payload/subsystems	Redundant power lines Backup batteries Fault-tolerant design Voltage and current sensing
Communication Failures	Loss of telemetry or data link between Module and Platform	Loss of control Inability to receive data from payload	Implement redundant communication channels
	Corruption of data in communication link due to radiation	Incorrect TM/TC	Implement error correction protocols
	Signal attenuation or interference disrupting transmissions	Reduced data quality Intermittent communication loss	Increase transmission power Error correction codes Auto re-transmission
	Corrupted or missing data due to transmission errors	Inaccurate or incomplete data Impact on Mission prosecution	Error detection and correction algorithms
Onboard Computer & Software	Software Crash	Loss of control Mission interruption	Watchdog timers Auto system restart Fail-safe modes

Category	Risks	Impact	Mitigation
	Algorithm Malfunction	Incorrect data processing Objectives compromised	Pre-flight testing In-orbit updates Real-time validation
	Memory & Data Corruption	Loss of critical mission data Command failures	EDAC Redundant memory Periodic scrubbing
	Command Execution Failure	Inability to perform maneuvers Function loss	Command verification protocols
Thermal Regulation Issues	Overheating/overcooling of components	Performance degradation Component failure	Thermal insulation Active thermal control
	Failure of heaters/radiators	Cannot maintain temperatures	Redundant TCS Alternate heating mechanisms
	Thermal expansion/-contraction	Structural damage Misaligned sensors	Low-expansion materials Compensate in design
	Freezing of instruments or optics	Functionality loss Reduced data quality	De-icing mechanisms Thermal blankets Heating elements

Table 2.4: Identified Risks for All phases

LEOP, Commissioning and Parking Orbit
During Launch the Module is Off and survival is granted by design and testing for the structural part while the thermal survivability is granted by the Platform Active Thermal Control.
The Module may encounter the following problems during the Commissioning and Parking Orbit phases:

Category	Risks	Impact	Mitigation
Initial Checkout Issues	Failure to power on	Mission startup failure Inability to proceed with operations	Implement redundant power systems Pre-launch functional tests Safe-mode implementation
	Unexpected power surges or undervoltage conditions	Potential damage to components	Use power conditioning units Surge protectors Voltage regulators
	Failure to establish an initial telemetry link	Loss of early mission diagnostics Inability to monitor spacecraft status	Implement redundant communication links Perform ground station verification before launch
Communications & Data Handling Failures	Incorrect or corrupted telemetry data transmission	Misinterpretation of spacecraft health status Incorrect decision-making	Use error correction codes (ECC) Implement redundant telemetry systems
	Command uplink failures	Inability to send commands Spacecraft may become unresponsive	Verify command execution via telemetry feedback
	Data retrieval and storage failures	Loss of mission-critical data Incomplete experiment results	Implement redundant data storage Periodic data integrity checks Onboard backups
	Units power-up failure or incorrect voltage levels	Sensor modules fail to operate Incorrect readings	Redundant power circuits Pre-flight validation In-flight recalibration procedures

Category	Risks	Impact	Mitigation
Sensors Calibrations	Failure of instrument calibration procedures	Inaccurate measurements Degraded data	Implement self-calibration routines Redundant reference sources
	Unexpected sensor noise or degraded performance	Reduced data quality Potential misinterpretation of results	Use filtering algorithms Monitor sensor health Redundancy in measurements

Table 2.5: Identified Risks for LEOP, Commissioning and Parking Orbit

Off-Nominal
Here, *Off-Nominal* refers to situations that arise from malfunctions occurring during nominal operations (described in section 2.5.1).

Category	Risk	Impact	Mitigation
Platform Motion / Attitude incompatibility with sensor detection and tracking	Failure to acquire the target	Impossibility to proceed to the next phase	Request platform motion / attitude adjustment
	Failure to identify the target	Impossibility to proceed to the next phase	Request platform motion / attitude adjustment
	Failure to track the target	Impossibility to proceed to the next phase Risk of Impact	Request platform motion / attitude adjustment
Sensors Malfunction / Degradation	Failure to acquire the target	Impossibility to proceed to the next phase	Perform sensor soft reset Sensors' software update Redundancy (Sensor Fusion) Use backup sensors

Category	**Risk**	**Impact**	**Mitigation Strategy**
	Failure to identify the target	Impossibility to proceed to the next phase	Perform sensor soft reset Sensors' software update Redundancy (Sensor Fusion) Use backup sensors
	Failure to track the target	Impossibility to proceed to the next phase Risk of Impact	Perform sensor soft reset Sensors' software update Redundancy (Sensor Fusion) Use backup sensors
	Acquiring a "false-positive" target	Missing mission objectives	Perform sensor soft reset Cross-check with alternative sensors Cross-check with previous detections Use AI-based classification models
Robotic Arms Mechanical Failure	Deployment/retraction failure	Arm unable to extend/retract properly Potential collision or damage	Use redundant deployment mechanisms Telemetry feedback Automated recovery sequences
	Malfunction of motors, controller or feedback sensor	Loss of precision Mission delay or failure Potential collision or damage Inability to perform operations	Controlled reattempt Use backup actuators Fault detection & isolation

Category	Risk	Impact	Mitigation Strategy
	Failed soft capture (End Effector Opening)	Loss of precision Mission delay or failure Potential collision or damage Arm unable to grasp the target	Controlled reattempt Use backup actuators Fault detection & isolation
	Failed separation (End Effector Closing)	Loss of precision Mission delay or failure Potential collision or damage Arm unable to release the target	Controlled reattempt Use backup actuators Fault detection & isolation
	Material fatigue	Structural weakening Reduced accuracy Component failure	Material selection & coatings Structural redundancy
Software and Control Issues	Incorrect trajectory execution	Misalignment Docking failure	Ground control overrides trajectory Real-time replan
	Loss of synchronization	Failed capture due to incorrect timing	Adjust software timing Recalibrate reference signals
	Latency in feedback loop	Delayed responses Potential misalignment	Use predictive control algorithms Adjust communication protocols

Table 2.6: Risks Identified for Nominal Operations

Decommissioning and Disposal

Category	Risk	Impact	Mitigation
Data Security	Residual mission data on payload	Data breach Potential mission compromise	Secure data erasure Encryption
Platform Dependency	Unexpected platform decommissioning or failure	Payload forced into early shutdown Mission disruption	Align decommissioning plans with platform lifecycle
Regulatory & Compliance	Non-compliance with disposal/end-of-life regulations	Legal consequences Future mission impact	Follow space debris mitigation guidelines Coordinate with platform provider
Environmental & Disposal	Uncontrolled disposal of platform and payload	Space debris creation Potential risk to other assets	Plan controlled deorbit Safe end-of-life strategy with platform provider
Operational	Payload systems active during decommissioning	Potential damage to platform or other assets	Implement shutdown and passivation procedures for robotic arms and sensors
Financial	Unexpected costs due to platform delays or extra deorbit maneuvers	Budget overruns	Allocate contingency budget Ensure clear decommissioning contracts

Table 2.7: Identified Risks for the Decommissioning phase

Programmatic Risks
Programmatic Risks cover Technical, Financial, Business and Logistic aspects by addressing uncertainties that can affect cost, schedule, and overall mission success. These risks arise from various factors, including budget constraints, supply chain disruptions, unforeseen technical challenges, regulatory and compliance requirements, and resource limitations. A comprehensive list is provided in the Risk Assessment Report compiled by the Project Manager.

Chapter 3

Vibration Analysis for Launcher Compatibility

As highlighted in the previous chapters, the objective of the Module is to maximize versatility and support a wide range of missions. To achieve this, the design must ensure survivability and operability under the most extreme expected conditions. Therefore, during the design phase, it is crucial to apply a Worst-Case Approach (WCA) by identifying scenarios that impose the highest demands on system performance. These scenarios serve as the baseline for designing a module that can withstand worst-case environmental, operational, and failure conditions while ensuring full functionality.
This approach should be applied to all aspects of Mission Design. While they all share the ultimate goal of defining the Worst Case scenario and consequently modeling the system accordingly, the way the Worst Case is determined varies significantly depending on the subsystem considered. This study, in particular, focused on two of them:

- Vibration Analysis for Launcher Compatibility
- Launch Adapter Ring (LAR) Analysis for End Effector Design

3.1 Vibration Analysis

The launch phase of a satellite is one of the most demanding stages of its mission since the vehicle is subjected to mechanical and acoustic environments that are extreme and include high levels of vibration, shock and aerodynamic pressure. The excitations are originated from various sources like rocket engine thrust oscillations, aerodynamic turbulence, and stage separation events. These include axial and lateral vibrations with transient shocks that can induce significant structural stresses

and resonance posing a serious risk to the satellite's integrity and functionality. The vibrations analysis at this stage is needed to determine the stresses to which the satellite will be subjected to determine the derived requirements and guarantee that the satellite is ready to withstand these harsh conditions and to function correctly once deployed into orbit.
The Launcher Analysis conducted for the ARCap module had the objective of determining its launch envelope. Starting with a predefined list of launchers, given below, and their respective manuals, a worst-case scenario was established for sine vibrations, acoustics, shock, and random vibrations.

- Sine Vibrations: simulate the steady oscillatory forces experienced during the operation of a launch vehicle, such as those caused by engine thrust or structural resonance. These vibrations are critical to consider in satellite module design to ensure components can withstand prolonged exposure to predictable oscillations without structural fatigue or failure.

- Acoustics: during liftoff, intense acoustic pressure from rocket engines creates high sound levels that can induce vibrations in satellite structures. Adequate design ensures that sensitive electronics, optical instruments, and payloads are shielded from these acoustic loads to prevent damage or misalignment.

- Shock: occur due to sudden events like stage separations, pyro-activations, or fairing jettison. These high-magnitude, short-duration forces can damage delicate components if not properly mitigated. Satellite modules must include shock absorbers or isolation mechanisms to protect critical systems.

- Random Vibrations: they arise from the turbulent environment during launch, including engine combustion and aerodynamic forces. These unpredictable, broadband vibrations require testing and design to ensure that satellite components can endure the dynamic environment without resonance or structural compromise.

During the ascent phase, depending on the events that occur, the following types of vibrations will be predominant [9]:

Ascent phase of launch vehicle	**Acoustics**	**Random Vibration**	**Sine Vibrations**	**Shock**
Liftoff	X	X		
Aerodynamics/Buffer	X	X		
Separation (stage, fairing, spacecraft)				X
Motor burn/Combustion		X	X	

Table 3.1: Sources of launch vehicle environments [9]

The environments of acoustics, random vibration, sine vibration, and shock are inherently non-deterministic and are generally not suitable for finite element analysis because they often involve frequencies up to several thousand Hertz, therefore they are defined globally through a statistically derived approach.
A common environmental specification is P95/50, which represents the level that is expected to exceed 95% of the data with 50% confidence. This is known as the Maximum Expected Environment (MPE), referring to a level that is typically not surpassed.
As anticipated, for each of these four categories, the worst-case scenario was determined by superimposing the vibration levels of each launcher and then extracting the highest value for each frequency. The results of this initial analysis served as the foundation for defining the combined requirements of the module in terms of vibration resistance.
Starting from a comprehensive list of all existing launchers in the world the following filters were applied:

1. LEO Payload shall be equal or superior to 1000 kg. This is justified as ARCap would be ridesharing with other satellites.

2. Last launch shall be after or equal to 2020.

3. Launcher must have an available user manual, either freely accessible or available upon request. Without it, it is not possible to perform the data analysis. This is by far the biggest filtering factor in this study

The final set of considered launchers for this analysis is presented in Table 3.2

Launcher	**Origin**	**Manufacturer**	**Launch site(s)**	**Date of 1st flight**	**Last Date of flight**
Falcon 9 [10]	US	SpaceX	Vandenberg, Cape Canaveral, Kennedy	2018	2024
Falcon Heavy [10]	US	SpaceX	Kennedy	2018	2024
Vega-C [11]	Europe, Italy	ArianeGroup, Avio	CSG	2022	2022
Ariane 6 [12]	Europe	ArianeGroup	CSG	2024	2024
Firefly Alpha [13]	US	Firefly Aerospace	VAFB, CCSFS	2021	2024
Epsilon [14]	Japan	IHI	KSC	2018	2022
H-IIA [15]	Japan	Mitsubishi	TNSC	2001	2024
Proton-M [16]	Russia	Khrunichev	Baikonur	2021	2021
Soyuz [17]	Russia	TsSKB-Progress	Baikonur, Plesetsk	2013	2024
Long March 3B [18]	China	CALT	XSLC	2007	2024
Long March 3C [18]	China	CALT	XSLC	2008	2021
Long March 2C [19]	China	CALT	JSLC, TSLC, XSLC	1982	2024

Table 3.2: List of considered launchers

3.1.1 Sine vibration

In launcher manuals the sine vibrations are divided into two types: lateral and longitudinal. The two, as defined in the ECSS-E-HB-32-26A – Mechanical shock design and verification handbook [20] are defined as follows:

- **Lateral sine vibrations**: These refer to sinusoidal oscillations applied perpendicular to the primary axis of the equipment, typically in the horizontal plane.
- **Longitudinal sine vibrations**: These are sinusoidal oscillations applied along the primary axis of the equipment, typically in the axial direction.

The superposition of all launchers lateral and longitudinal vibration is displayed below:

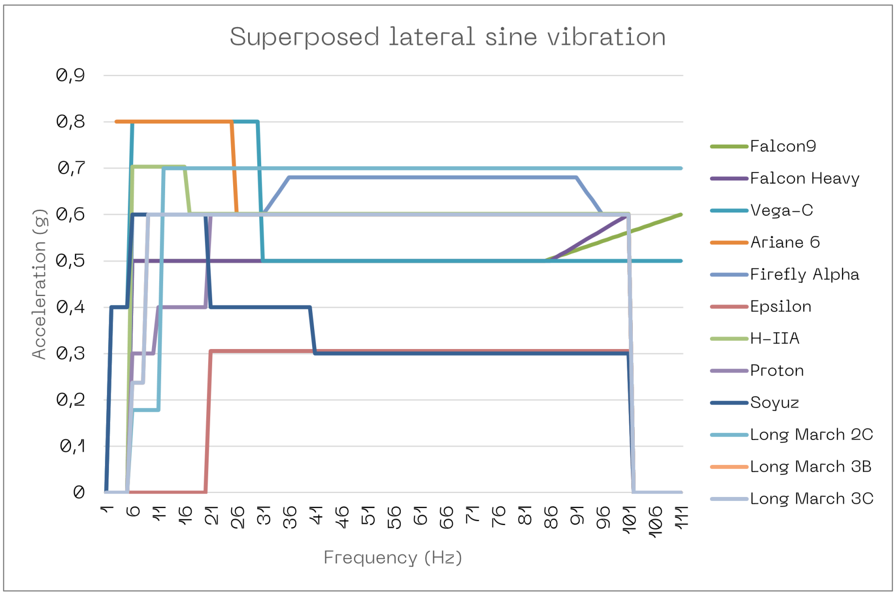


Figure 3.1: Lateral Sine Vibration superposition

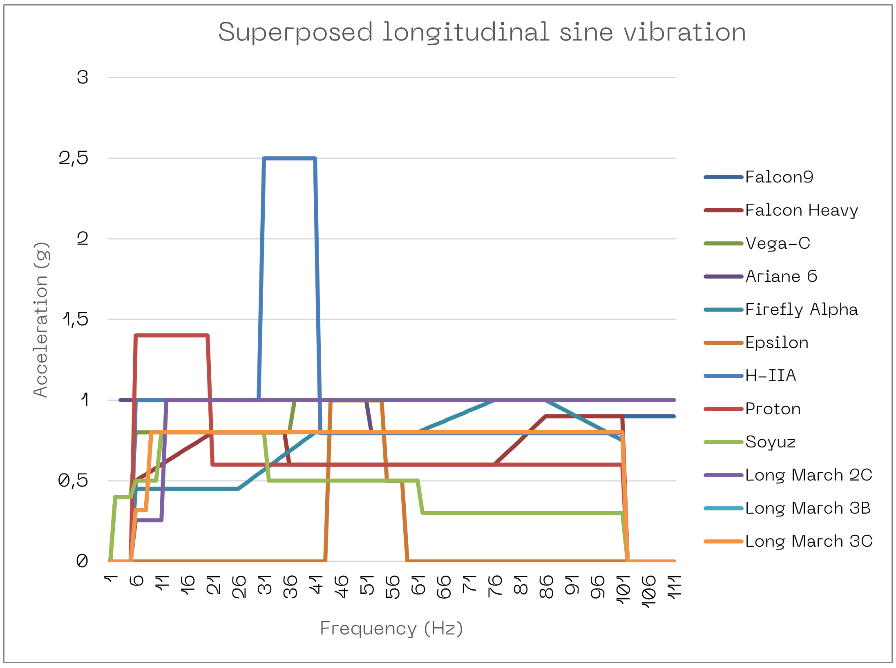


Figure 3.2: Longitudinal Sine Vibration superposition

The result of this overlap was the determination of the worst-case scenario for both cases, presented below both as a table and as a vibration profile:

Frequency (Hz)	Lateral sine vibrations (g)	Longitudinal sine vibrations (g)
0	0	0
1	0.4	0.4
2	0.8	1
4	0.8	1
5	0.8	1.4
19	0.8	1.4
20	0.8	1
29	0.8	1
30	0.7	2.49
40	0.7	2.49
41	0.7	1
110	0.7	1
111	0	1
115	0	1

Table 3.3: Sine vibration profile.

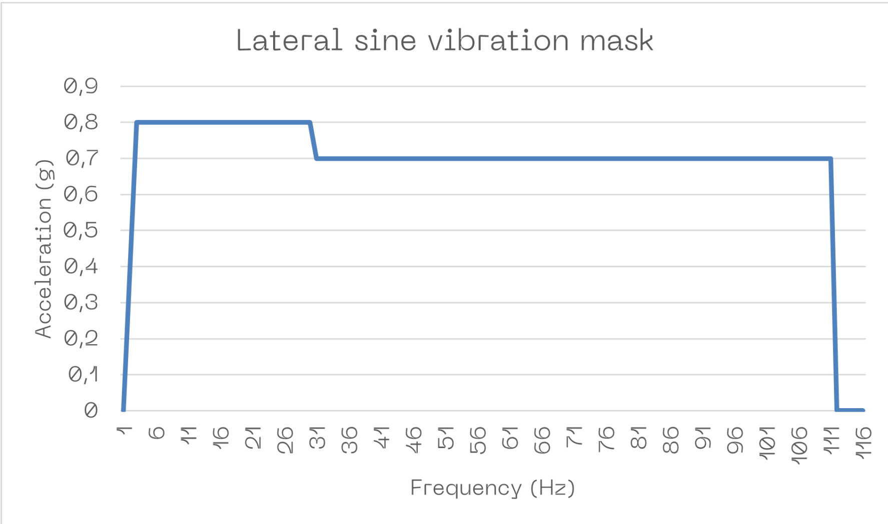


Figure 3.3: Lateral Sine Vibration Worst Case Scenario

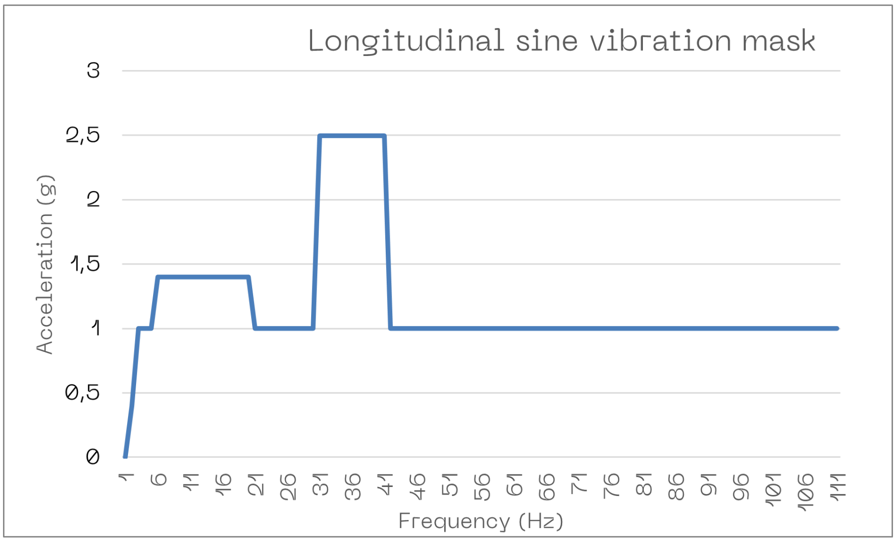


Figure 3.4: Longitudinal Sine Vibration Worst Case Scenario

3.1.2 Acoustics

As for the Acoustics, the result of the superimposition is the following:

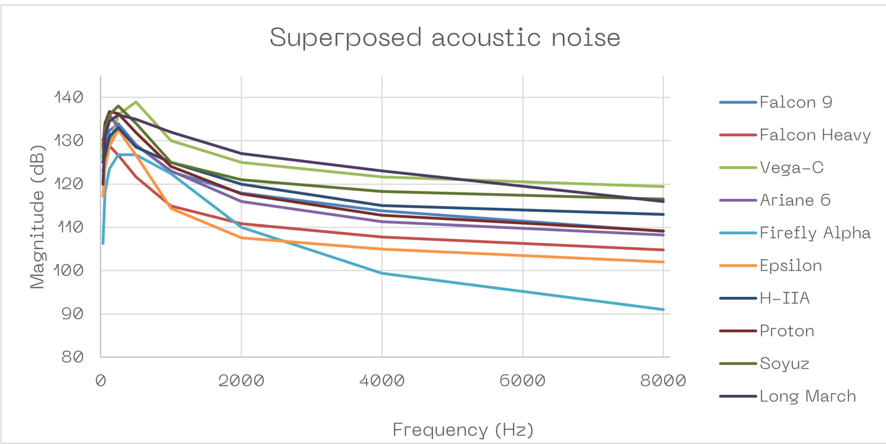


Figure 3.5: Acoustics

This overlap allowed the identification of the worst-case scenario, presented below both as a table and as a vibration profile:

Frequency (Hz)	Magnitude (dB)
31.5	130.3
63	134
125	136.7
250	138
500	139
1000	132
2000	127
4000	123
8000	119

Table 3.4: Acoustics

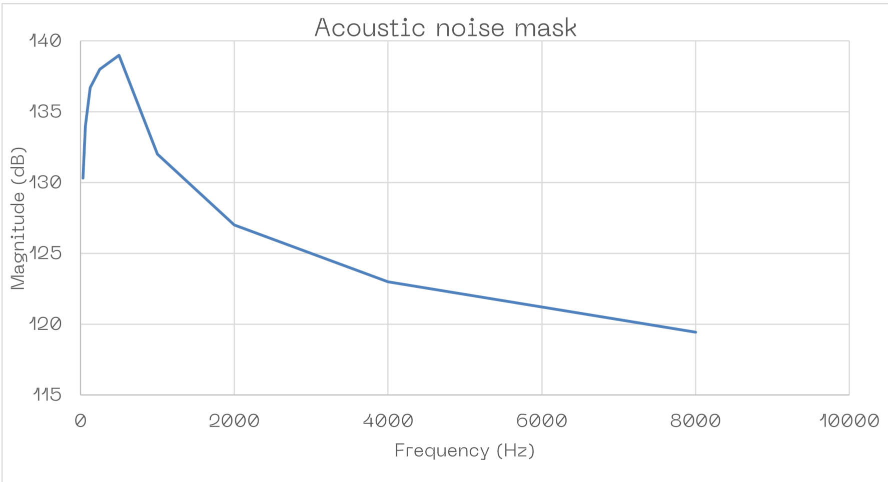


Figure 3.6: Acoustics Worst Case

3.1.3 Shock

For the Shock vibrations, the result of the superimposition is as follows: The result of this overlap was the determination of the worst-case scenario, presented below both as a table and as a vibration profile:

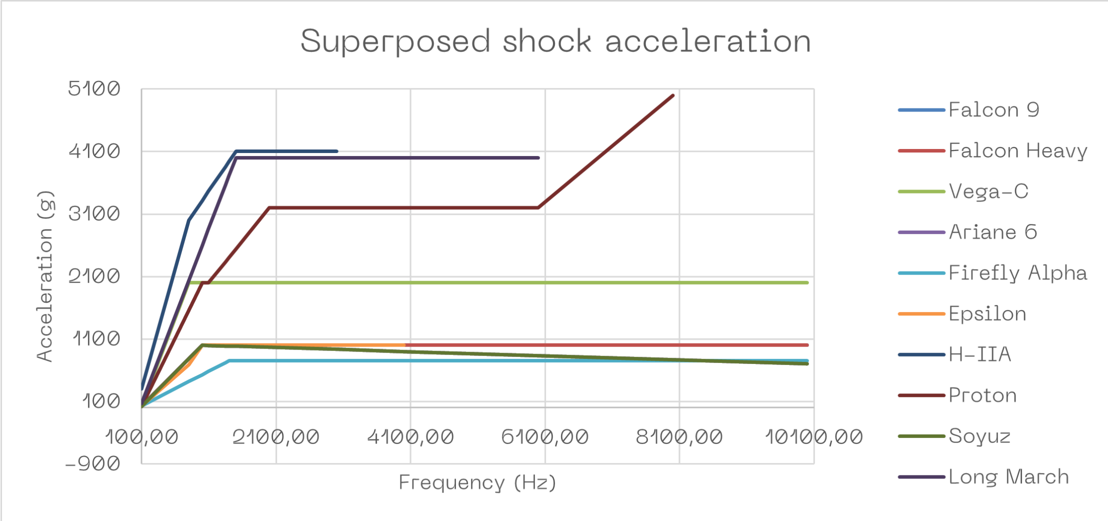


Figure 3.7: Shock Vibrations

Frequency (Hz)	Acceleration (g)
100	300
800	3000
1000	3314
1094	3463
1343	3853
1400	3942
1500	4100
2000	4100
3000	4100
4000	4000
6000	4000
8000	5000
10000	2000

Table 3.5: Shock Vibrations

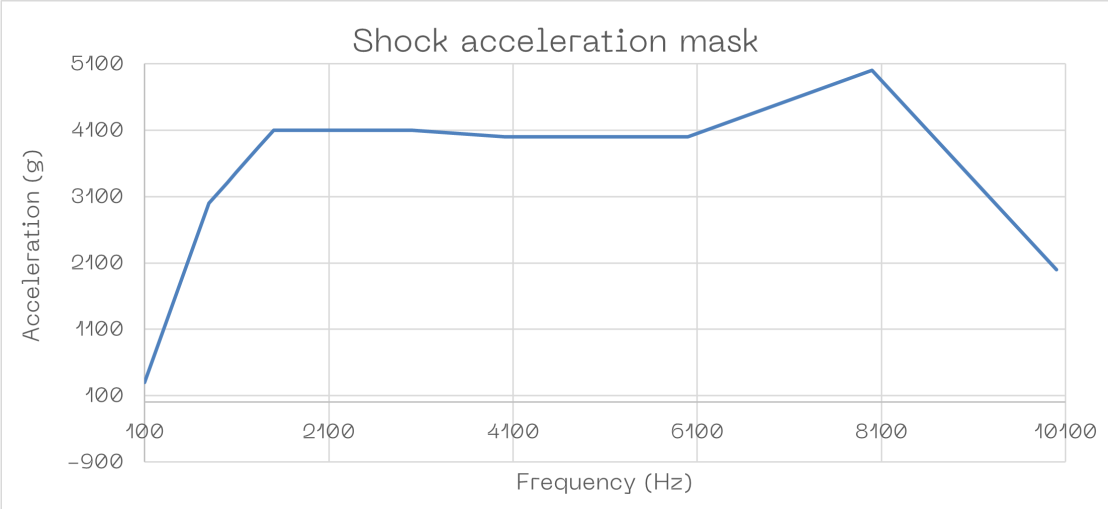


Figure 3.8: Shock Vibrations Worst Case

3.1.4 Random

As for Random vibrations, the result of the superposition is the following:

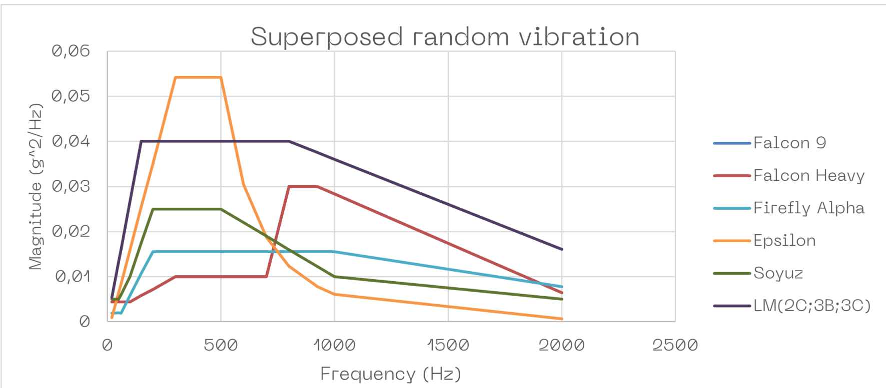


Figure 3.9: Random Vibrations

Frequency (Hz)	**Magnitude (g^2/Hz)**
20	0.00540
50	0.01338
60	0.01605
100	0.02669
150	0.04000
200	0.04000
225	0.04000
300	0.05420
500	0.05420
559	0.04000
600	0.04000
700	0.04000
800	0.04000
925	0.03751
1000	0.03602
2000	0.01610

Table 3.6: Random Vibrations

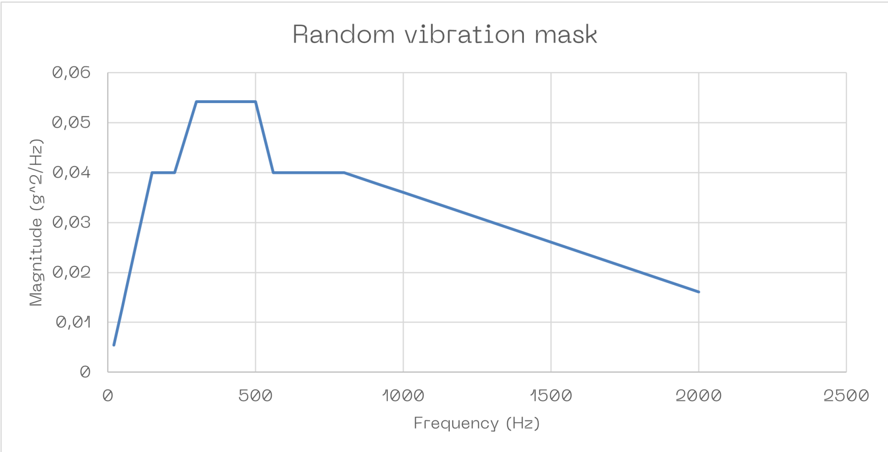


Figure 3.10: Random Vibrations Worst Case

3.2 Derived Requirements

The analyses performed above have been used afterward as a baseline to derive the requirements related to vibrations resistance for the Module. At this phase of the project (Phase 0/A), it is important to define the requirements at System level, to identify which characteristics the Module should exhibit as a whole. These requirements are presented in Table 3.7. Afterward they will be used as parent requirements for the subsystem ones, defined at unit level. As for the categorization of such requirements, considering as reference the ECSS-E-ST-10C - System Engineering general Requirements [21] they are system requirements - since they all apply to the whole module - falling into the "Physical Requirement" category since they refer to the capability of ARCap to withstand the vibrations to which it will be subjected during the launch phase.

The verification methods for this requirements are selected considering the following list from the ECSS-E-ST-10-02C - Verification [23]:

- test (including demonstration): measuring product performance and functions under representative simulated environments
- analysis (including similarity): performing theoretical or empirical evaluation using techniques agreed with the Customer
- review-of-design: shall consist of using approved records or evidence that unambiguously show that the requirement is met
- inspection: visual determination of physical characteristics

All the requirements considered in this section are physical one, therefore the verification method should be test to verify the Module ability to withstand the vibration environment. Testing will be performed in the later development stages (Phase D).

Considering the development of the model, the different versions that will be developed are:

- **Engineering Model (EM)**: early version of the system used to verify that the design meets the functional and performance requirements. The EM is typically used in the early stages of development to test key subsystems and identify potential design flaws. While the EM may not be fully representative of the final design, it helps engineers evaluate the system's basic functionality and ensures that critical elements are working as intended. The EM is not intended for launch and typically uses non-flight-qualified materials
- **Engineering Qualification Model (EQM)**: a version of the system that is fully representative of the flight design. Its primary purpose is to demonstrate compliance with the qualification requirements for spaceflight. The EQM undergoes rigorous testing, including thermal cycling, vibration, shock, and vacuum tests, to verify that the system can withstand the harsh conditions of launch and the space environment. The results from these tests confirm that the design is flight-ready, meeting all operational and safety requirements

Type	Requirement
Sine	The ARCap module shall withstand sine vibration loads up to the worst-case profile identified and shown in Table 3.3 without structural failure or functional degradation. The qualification test shall be conducted in accordance with ECSS-Q-ST-10-03C [22], using the direction-dependent profiles. The sweep rate shall be 2 octaves per minute as per ECSS standards, and the vibration shall be applied to each axis separately.
Acoustics	The ARCap module shall withstand the acoustic environment corresponding to the worst-case profile identified and shown in Table 3.4, without structural failure or functional degradation. The qualification test shall be conducted in accordance with ECSS-Q-ST-10-03C [22], using the identified octave-band sound pressure levels. The acoustic noise shall be applied in a reverberant chamber or equivalent setup, and the exposure duration shall follow ECSS standard practice.
Shock	The ARCap module shall withstand mechanical shock loads corresponding to the worst-case Shock Response Spectrum (SRS) identified and shown in Table 3.5, without structural failure or functional degradation. The qualification test shall be conducted in accordance with ECSS-Q-ST-10-03C [22], using the identified shock profile. The shock profile shall be applied as a series of pulse excitations, with the peak acceleration and duration as specified in the referenced table.
Random	The ARCap module shall withstand random vibration levels corresponding to the worst-case Power Spectral Density (PSD) identified and shown in Table 3.6, without structural failure or functional degradation. The qualification test shall be conducted in accordance with ECSS-Q-ST-10-03C [22], using the identified PSD levels. The vibration shall be applied in a random excitation mode, with the total test duration and level profile as specified in the referenced table.

Table 3.7: Vibration Environment Requirements

- **Flight Model (FM)**: the final, fully functional hardware that will be used during the actual mission. It is built using the final materials, components, and design specifications intended for flight. The FM undergoes final integration and pre-launch testing to ensure that all systems are operational and ready for deployment. This model is the one that will be launched into space, representing the fully validated and operational version of the spacecraft. It is the culmination of the entire design and testing process, after the EQM has demonstrated the system's flight readiness

Vibration testing will thus be performed on the EQM in accordance with:

- ECSS-E-ST-10-03C (Testing) - defines the test conditions, procedures and acceptance criteria for mechanical testing
- ECSS-E-ST-32-10C (Mechanical Vibration Design & Verification) - provide requirements for designing and verifying mechanical structures
- ECSS-E-ST-32-08C (Shock Testing) - defines requirements for shock testing by describing setups, equipment and qualification level
- ECSS-E-HB-32-26A (Random Vibration & Acoustic Test Handbook) - provides guidance for conducting random vibration and acoustics tests

Chapter 4

LAR Analysis and End Effector Design

This part of the study focuses first on the analysis of launcher adapters, and specifically the Launcher Adapter Ring (also called simply launcher Ring or passive ring). This represents the interface - attached to the satellite - to the deploying mechanism. The scope is to assess potential design uniformity across different launch vehicles.
To do so it is important to consider the deployment mechanism used. Two main types of separation systems were identified, based on satellite size: Clamp Band Separation System and Lightband®Separation System.
Information was gathered from all the user manuals of the launcher presented above in Table 3.2, to determine acceptable solutions for grasping the ring with robotic arms. In line with the above-mentioned scope, the analysis has indeed identified similarities in the cross-section of the investigated passive rings, which can be utilized for the preliminary design of robotic arm end effectors.
Objective of the second phase of study was to identify, based on the analysis of launcher adapters, the most suitable types of end effectors in terms of compatibility and effectiveness in achieving the designated goal: gripping the launcher adapter ring.
After presenting a categorization of existing types of end effectors - mechanical claws, vacuum-based, magnetic, microspine, snare, gecko-inspired adhesive-, one —mechanical claw—was selected as the best candidate.
Subsequently, an analysis was conducted to determine whether two or three robotic arms would be more suitable. It was concluded that three arms are optimal for effectiveness and redundancy. After determining the worst cases in terms of launcher adapter ring cross section - biggest and smallest - three different designs has been proposed and compared.

The list of adapters used among the launchers considered is presented below:

Launcher	Separation System	Adapter Name
Ariane 5	Clamp Band	PAS 937S, PAS 937C, PAS 1194VS, PAS 1194 C, PAS 1194CS, PAS 1666 MVS, PAS 1666 S, PAS 2624 VS
	4 bolts with pyro nuts	PAS 1663
Vega-C	Clamp Band	Provided by Arianespace & RUAG PAS 381/610
	Lightband	PSC Mk II MLB series (ø 610, 381, 330, 298 mm)
Falcon 9	Clamp Band	EELV 1575, 2624
Firefly Alpha	Clamp Band	Customer provided
	Lightband	Planetary Systems Lightband®
	Others	Dassault ASAP 5, ISIPOD CubeSat Deployer
Soyuz	Clamp Band	PAS 937 S, PAS 1194 VS, PAS 1666 MVS
Proton	Clamp Band	937 VB, 1194 VX, 1194 VS, 1666 V, 1666 HP
H-IIA	Clamp Band	937 LS-H, 1194 M, 1194 LS-H, 1666 LS-H
Epsilon	Lightband	937 M
Long March 3A	Clamp Band	937 B, 1194, 1194 A

Table 4.1: Launchers considered and their respective LARs

These data has been used as baseline for the Worst Case definition and End Effector preliminary design, presented in the following sections.

4.1 LAR Analysis

Through this analysis, two main types of deployment mechanisms have been identified, where the S/S can securely capture the payload. The latter is conceived to support and hold the satellite during launch and safely release it into orbit, and due to its structural strength can now be used for other purposes. Clamp Band Separation Systems are versatile mechanisms used across a wide range of satellite sizes, from small satellites (smallsats) to very large satellites and Lightband Separation Systems are used for Nano, Micro and Mini Satellites. In detail:

- **Clamp Band Separation System (CBSS)**: this mechanism is used in launch vehicles. The system employs a clamp band to maintain a high-tension connection between two key interface components: the active ring and the passive ring
  - *Active Ring*: The structural element fixed to the payload adapter of the launch vehicle, which houses the actuation mechanisms for clamp band release.
  - *Passive Ring*: designed to interface with the active ring and hold the payload in place until separation.

  During separation, the Clamp Band Opening Device (CBOD) is activated to release the tension in the clamp band, disengaging the connection between the active and passive rings.
  A simplified scheme and a CAD of this deployment mechanism are presented below:

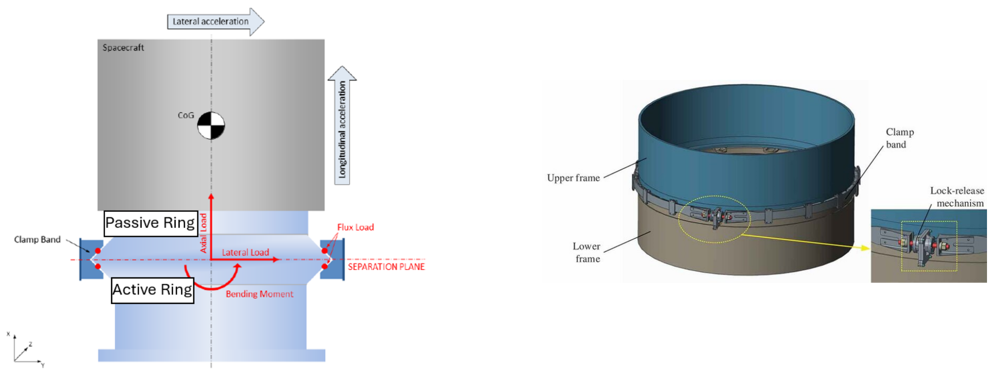


Figure 4.1: Clamp Band Separation System and CAD Model

- **Lightband®Separation System** the payload's passive ring and the launch vehicle's active ring are held together by preloaded latches. At separation, actuators release the latches, and springs push the payload away smoothly and without spin. It is ideal for small satellite for its light weight, reliability, and reusability. Furthermore *it eliminates the two major problems of standard separation systems: fracturing and shock from the explosives used to break*

open the band to release the satellite [24].
A CAD model of such system is presented below:

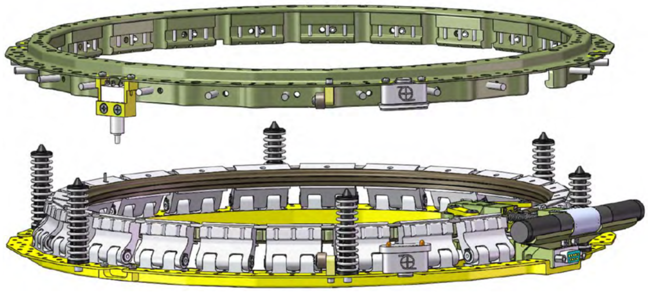


Figure 4.2: Lightband Separation System CAD Model

4.2 End Effector Design

4.2.1 Categorization

For the categorization and the trade-off between the different end-effector types, the following study has been used as reference: *Multicriteria Analysis of Robotic End-Effectors for Grasping Space Debris* by Orzechowski and Bazzocchi [25].
In this section characteristics of each of the end effectors are presented

End-effector Type	Specs
Mechanical Claws	Three or more robotic fingers for grasping larger masses. Operate via grasping or pinching. Controlled through force stiffness, with/without spring damping. Configurable in number of prongs and grasping radius for mission constraints.
Vacuum Based (*)	Use suction techniques to latch onto targets. Superior for flat surfaces compared to claws. Less effective for irregular shapes. Fewer moving parts, reduced complexity, limited use in vacuum/on-orbit.
Magnetic	Grasp ferromagnetic targets using electromagnetic currents. Attraction or repulsion by polarity change. Electro-permanent designs for precise pick/release. Can capture translational/yaw velocity data. Useful for magnetic latching and docking.

Microspine	Numerous protruding spines mimic insect/arthropod grips. Developed by NASA JPL. Tested on rocks, trees using steel prototypes. Yet to be validated for moving targets or diverse materials.
Snare	Three or more wires wrap around and constrict the target. Used on ISS for servicing, assembly, and maintenance. Proven effectiveness with significant flight heritage.
Gecko Inspired Adhesive	Adhesive film enhances surface grip. Can be applied to claws or flat surfaces. Adapts to curved shapes, improving grasp. Studies show better performance with adhesive films.

Table 4.2: End Effector categorization

(*) the vacuum based was excluded from the analysis because of its limited applicability in vacuum or on-orbit environments

The analysis was conducted considering three operational scenarios:

- On Orbit Servicing (OOS)
- Rocket Body grasping
- Debris Grasping

Considering that the ARCap module, for which this end effector analysis is conducted, could in the future potentially be used in all the scenarios above, this paper works as a good foundation for this study. The study presented in the paper shown the following characteristics for each end effector type:

End-effector Type	Specs
Mechanical Claw	Performed best based on the criteria and problem specifications for the operational scenarios. The mechanical claw end-effector grouping has a high TRL (∗). It can exert a relatively large attachment force and has the greatest performance for the scope of this study. However, it requires more power and is more complex.

End-effector Type	**Specs**
Magnetic	Would be a fitting solution for rocket body grasping. However, it is less effective for debris removal if the debris did not have magnetic properties or a magnetic grasp point.
Microspine	Would perform well for grasping orbital debris and rocket bodies. However, it would not be as favorable for on-orbit servicing due to the alteration to the target. It may also have difficulty grasping onto debris objects with smooth surfaces.
Snare	May perform well for on-orbit servicing (OOS) depending on the target design. However, it may have difficulty grasping onto non-cooperative debris and rocket bodies.
Gecko-Film Adhesive	Relatively simple, requires less power, and has a relatively small volume and mass.

Table 4.3: End Effector types comparison

(*)TRL: Technology Readiness Level: a defined measure of the maturity level of a specific technology as defined by the National Aeronautics and Space Administration (NASA)

The best performing end effector type in the scenarios listed above was the Mechanical Claw one.

Moving to the specific case of the ARCap module, this type seems to be the most suitable for grasping the passive ring due to its ability of applying a high force and being, in term of design, highly customizable.

4.2.2 Number of Robotic Arms

Before moving to the end effector design it is important to consider how the module can effectively grip the ring. To do so it is necessary to define the ideal number of robotic arms. Referring to the categorization presented in *Current Designs of Robotic Arm Grippers: A Comprehensive Systematic Review* by Hernandez, J.; Sunny, M.S.H.; Sanjuan, J.; Rulik, I.; Zarif, M.I.I.; Ahamed, S.I.; Ahmed, H.U.; Rahman, M.H [26], given the circular shape of the launcher adapter ring, two gripping modes have been analyzed:

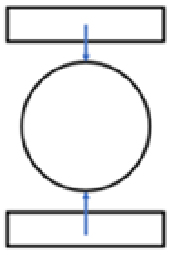
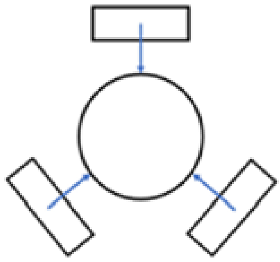
Gripping mode	Parallel or flat	Spherical
# of arms	2	3
Layout		

Table 4.4: Parallel and Spherical gripping mode

To identify the best solution, strengths and weaknesses of each layout have been identified

# of arms	**Pros**	**Cons**
Two	Lower production and operational cost; requires less physical space; simpler control systems; lighter, reducing overall module weight.	Requires more power per arm; less stable grip for complex operations; limited redundancy in case of failure; limited versatility for multitasking.
Three	Greater reliability due to redundancy; distributes workload, reducing power demand per arm; firmer grip and improved precision; greater dexterity and operational versatility.	Higher production and operational costs; occupies more space in the module; increased control complexity; heavier, increasing module weight.

Table 4.5: Comparison of two-arm and three-arm gripping systems

The primary considerations in this study are the firmness of the grip, which is critical for securely attaching to the launcher's adapter ring and enabling on-orbit servicing, and the reliability of the robotic system, given the ARCAP module's intended operational lifespan of five years.
Considering these two factors, the solution with three robotic arms appears to be the most suitable.

4.2.3 End Effector Preliminary Design

To grip the ring more effectively and be able to exert the strength needed, the ring is going to be gripped both from the outer part (as shown in Table 4.4) and the inner part of the ring. This means that each robotic arm will have an end effector capable of grabbing the ring simultaneously in the inner and outer parts. Therefore, a parallel gripper design is investigated.
To create an end effector able to pinch effectively the ring it is necessary to consider its cross section. Data from the User Manuals was gathered, to define shape and dimensions of all the LARs, previously presented in Table 4.1.
A worst-case scenario approach has been used. The sections were overlaid, and the external contour resulting from the overlap was traced. This process defined the biggest and smallest profile created by the superimposition. Since the sources were not providing all the measures, the one missing were deducted considering the proportions in the original drawing and the scale used.
The main focus during this study was on Ariane 5, Proton,Soyuz, H-IIA and Epsilon since detailed data on their launcher adapter data were available. Result of the superimposition is presented below:

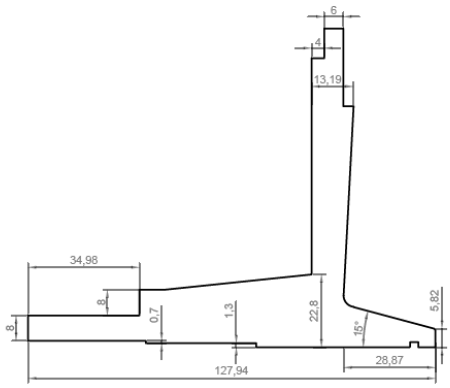
Case	**Cross Section**
Worst Case - outer outline	
Worst Case without 2624 - outer outline(*)	

Table 4.6: Biggest Envelope Worst Case

(*)Since this section is the only one significantly differing in size and shape, the analysis has been conducted both with and without it being superimposed for a comprehensive evaluation.

Same has been done with the inner outline, obtaining the worst case in terms of the smallest cross section.

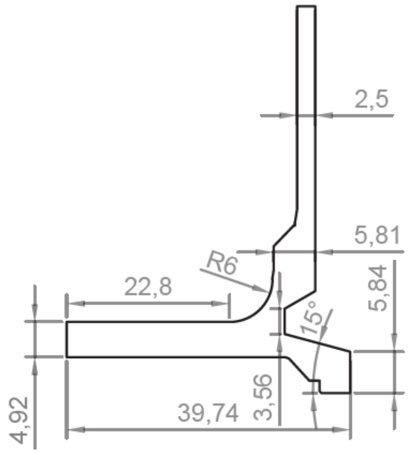
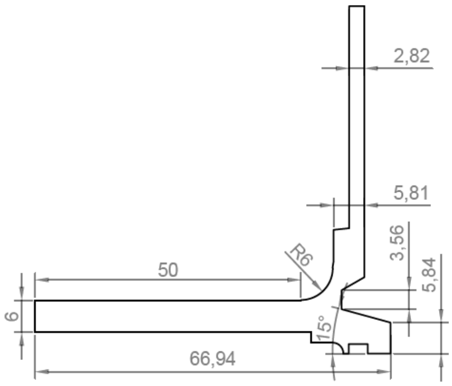
Case	Cross Section
Worst Case - inner outline	
Worst Case without Epsilon - inner outline(**)	

Table 4.7: Smallest Envelope Worst Case

(**)Since this section is the only one significantly differing in size and shape, the analysis has been conducted both with and without it being superimposed for a comprehensive evaluation.

Once the worst case both for biggest and smallest cross section have been identified the end effector claw shape is investigated.

4.2.4 Actuation Mechanism

The actuation mechanism needs to provide a firm grip, be reliable and be compatible with the designed claws. Considering the result of the analysis a good candidate is

represented by parallel grippers with linear guide mechanism.
A simplified visual representation of it is presented below:

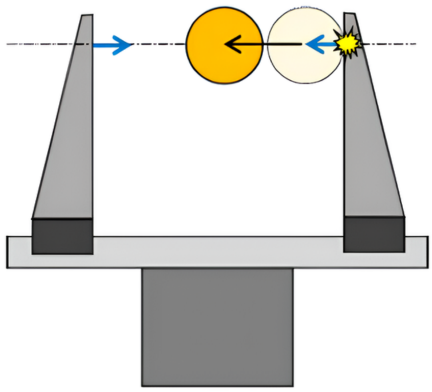


Figure 4.3: Parallel Gripper

This allows to move the two claws on a horizontal plane effectively gripping the ring between them by applying a strong force - up to 3000 N for the heavy duty ones.
To realize this linear actuation, several solutions can be considered:

- Hydraulic Actuators
- Electric Linear Actuators
- Pneumatic Actuators
- DC Motor with Lead/Ball Screw

To compare them a trade-off analysis has been conducted considering the following criteria:

- Compactness
- Precision
- Reliability
- Force output/mass
- Cost
- Thermal resistance

- Durability

To each of the criteria a value from 1 (very low) to 5 (very high) has been assigned:

Criteria	Hydraulic	Electric Linear	Pneumatic	Motor with Lead-/Ball Screw
Compactness	2	5	3	5
Precision	3	5	2	5
Reliability	3	5	2	5
Force Output/Mass	5	3	2	4
Cost(*)	2	4	5	4
Thermal Resistance	2	4	2	4
Durability	3	5	2	5

(*)in this case 1=very expensive and 5=very inexpensive

Table 4.8: Actuator Types Trade Off

Result of this trade off is that the best candidate for the criteria considered is a ball screw actuator, an example of this system is shown below:

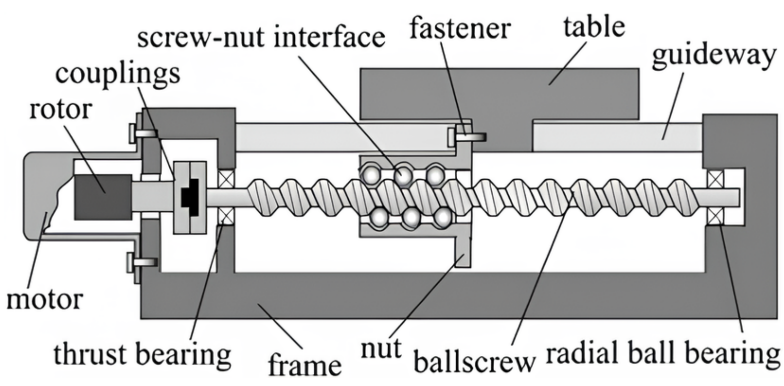


Figure 4.4: Screw nut actuation mechanism scheme

This system performs excellently in in precision, compactness, reliability, and durability, with decent force output/mass, making it a balanced choice for applications requiring moderate force and high accuracy.
So the baseline for the design proposed is: claw gripper with a linear electric ball screw actuator actuator in the base moving the claws (Figure 4.3).
Three different configurations have been designed and considered:

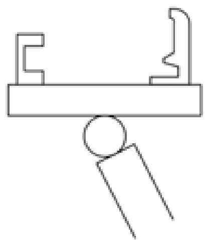
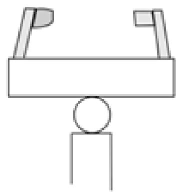
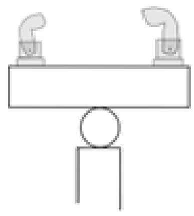
		
SOLUTION A • 2 contact points • 1 linear actuator • 2 moving elements	SOLUTION B • 3 contact points • 2 linear actuators moving 5 elements (2 claws + 3 claw tips)	SOLUTION C • 3 contact point • 1 linear actuator moving 2 elements • 3 motors moving 3 rotating fingers

Table 4.9: Solutions Overview

The main difference between A and the other two is the number of contact points. Since three contact points allow for a firmer gripper two different solutions (B and C) have been considered. Before comparing them, each of the three is presented in the next section.

SOLUTION A

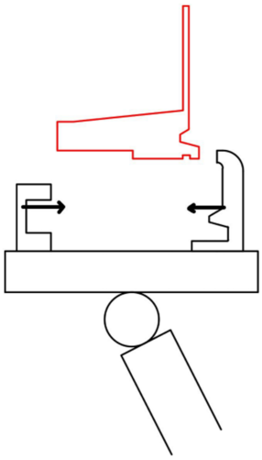
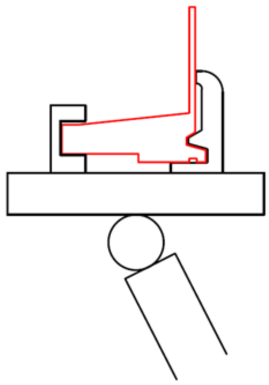
Open Position	Closed Position
	

Table 4.10: Solution A overview

This solution is mechanically the simplest considered since it presents just two claws, that lock the adapter ring in between them. One of the crucial aspects to be considered is the shape of the claws that need to adapt and follow closely the shape of the cross section, to ensure a firm grip.

Claw Shape

The goal of this section is to identify a claw shape compatible with most of the worst-case scenarios defined above. To do so the common elements among them have been identified and are highlighted in Table 4.11 The main similarity across all four is, for the right side, having an inclined surface at 15-degree angle (highlighted in yellow) and a flange of around 5.8 mm (highlighted in orange). As for the left side – the inner part of the ring - all of them share the same rectangular shaped section, but while three have a flange of the same size on the left (highlighted in green), the last one – worst case in term of the outer outline has a significantly larger flange. As evident the right and left claws will differ in shape since the outer and inner parts of the rings present a very different structure and size. The right side – outer part of the rings – appears to have very similar shape, but significant size difference between the smallest and the biggest outline. Therefore, two solutions have been considered:

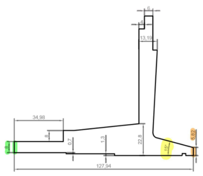
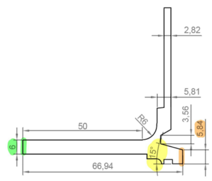
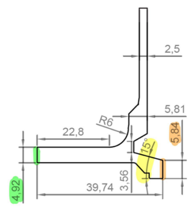
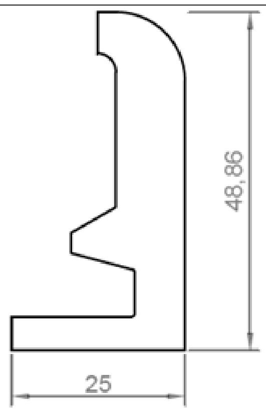
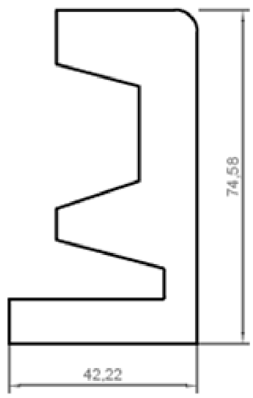
<table>
<tr><th>Worst Case without 2624 (outer outline)</th><th>Worst Case (outer outline)</th><th>Worst Case without Epsilon (inner outline)</th><th>Worst Case (inner outline)</th></tr>
<tr><td></td><td></td><td>
</td><td>
</td></tr>
</table>

Table 4.11: Cross Sections' comparison

<table>
<tr><th>Worst Case - inner outline</th><th>Worst Case - outer outline</th></tr>
<tr><td>
</td><td>
</td></tr>
</table>

(*)dimensions presented in the drawings are just a reference of the size difference

Table 4.12: Solution A right claw

For the left side the shape of all 4 worst cases the same – rectangular section- therefore a C-shaped end effector can effectively grasp all four. The only notable difference is with Ariane's 2624, as highlighted in the section above, which requires a bigger left claw – around double the size. The table below presents the design and the corresponding dimensions, for the two cases, with and without considering Ariane's 2624:

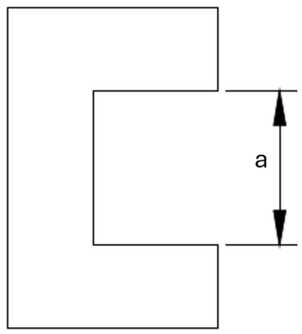
	- Without 2624: $a = [5; 9]$ mm - With 2624: $a \sim 21$ mm

Table 4.13: Solution A left claw

SOLUTION B

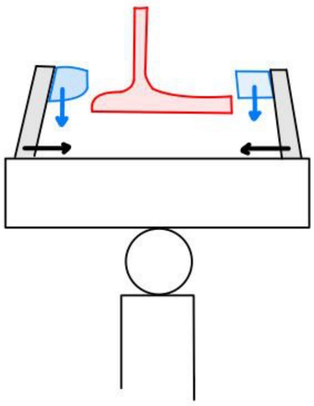
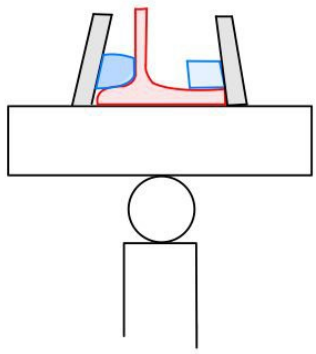
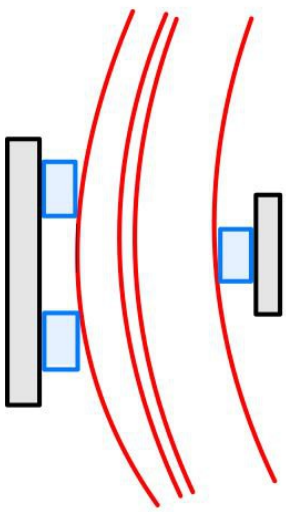
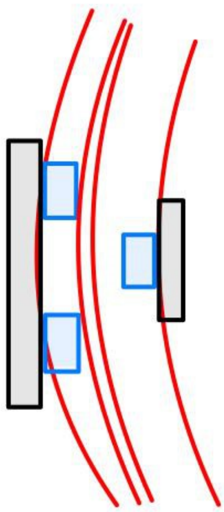
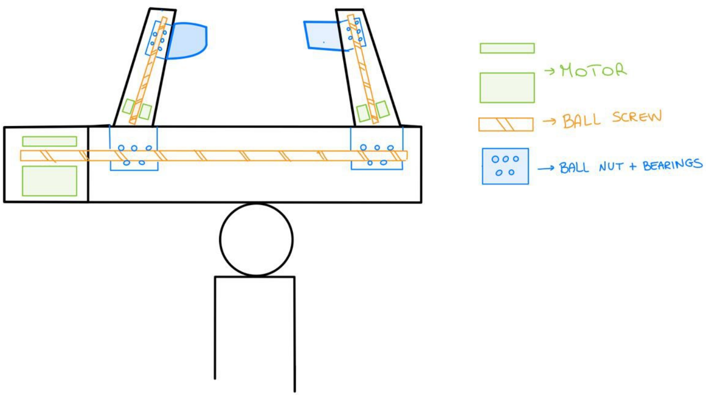
Open Position	Closed Position
	
	

Table 4.14: Solution B overview and OVERSIDE view

Increasing the number of contact points, going from two to three allows having a

firmer grip because it locks the rotation around the central axis of the end effector. Here the moving parts are the two claws, each with a movable protrusion.. All of them are actuated by linear ball screw actuators.
The idea is to grab the ring along the direction parallel to the end effector base - and then bring it towards the base by moving the protruding elements - referred to as "claw tips" from now on.
This allows to first do a "soft" capture by closing the two claws not allowing the ring to escape and then securely lock it in place with the claw tips. A scheme of the end effector and its actuation mechanism is presented below.



**the left claw has 2 claw tips (as is evident from the overside view in Table 4.14)*

Figure 4.5: Solution B actuation mechanism

The two fingers on the left claw - grabbing onto the outer part of the ring - can be moved together - by mounting them together on a single plate - or independently. In the latter case, an additional motor or a more complex linear actuation mechanism would be needed to eventually disengage one of the fingers.
This solution allows for a high force output due to the use of ball screw actuators but the fact that all the moving parts are linearly actuated makes it more difficult to adapt to the circular shape of the ring. Therefore the structure of the End Effector, especially the outer claw with the two claw tips has to be designed to mimic, while locked, the shape of the ring.

SOLUTION C

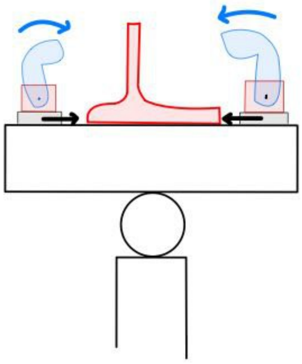
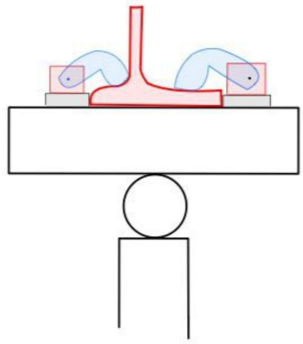
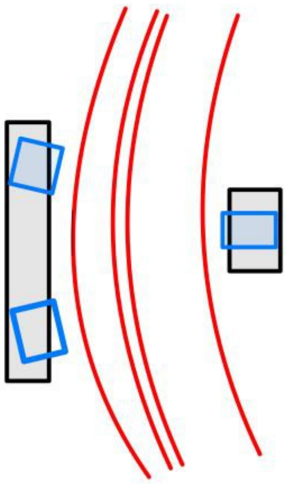
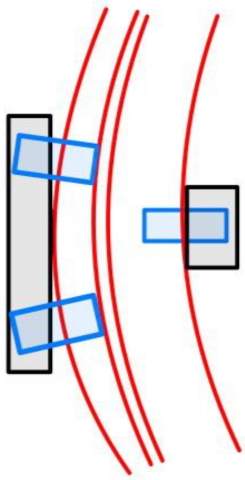
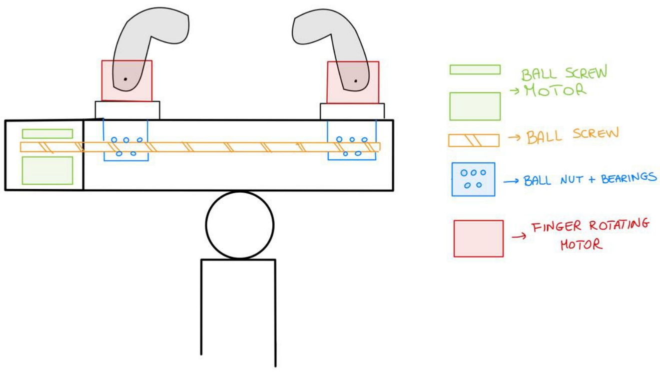
Open Position	Closed Position
	
	

Table 4.15: Solution C overview and OVERSIDE view

Here again, a 'soft' capture is performed first. The difference is that this is achieved

by all the moving parts working together by closing the two claws and partially rotating the fingers. Then the three rotating fingers, lock the adapter.
Having fingers that rotate allows for a smaller End Effector size in the direction perpendicular to the base and moving them independently allows better adaptation to the adapter ring since they can also be actuated asymmetrically.



**the left claw has 2 claw tips (as evident from the overside view in Table 4.15)*

Figure 4.6: Solution C actuation mechanism

4.2.5 Contact Surface

For all the solutions, a soft material should be utilized on the contact surface of the gripper (both claws and the base). This allows for a firmer grip – by increasing friction and reducing slippage – and better adaptability to the launcher adapter ring shape.
Two options that can be considered, and are already used in space applications are Silicone Elastomers and Rubber Composites such as Thermoplastic elastomers (TPE).
Their characteristics are highlighted in the table below:

	Silicone Elastomers	**Thermoplastic Elastomers (TPE)**
Temperature Range	-100°C to 250°C	-40°C to 150°C
Thermal Stability	Excellent high-temperature stability	Good thermal stability
Flexibility/Elasticity	Highly flexible and retains shape	Flexible while retaining strength
Wear Resistance	Moderate to high wear resistance	Excellent abrasion resistance
Adaptability	Conforms well to surfaces for better grip	Customizable textures for grip

Table 4.16: Comparison of Silicone and Thermoplastic Elastomers

The comparison between silicone elastomers and thermoplastic elastomers is based on technical data from Wacker Chemie AG [27], Avient Corporation's *TPE performance guide* [28], and a comparative analysis presented in Avient Corporation's *TPEs and LSRs: A Comparative Guide* [29].

4.3 Solution Comparison

SOLUTION	**Pros**	**Cons**
A	- Mechanically simpler (only 1 linear actuator) - Fewer components - Easier to model and control - Potentially more robust due to fewer failure points	- Only 2 contact points → allows rotation around EE central axis - Claw shape must match target geometry precisely (less adaptable) - Less stable grip under external disturbances - Less fault-tolerant — failure of the linear actuator = total failure
B	- 3 contact points: prevents rotation around EE axis - Simpler claw shape, adapts through linear movement - Better adaptability to ring shape: more moving elements - Potential redundancy: grip may still hold if one actuator fails	- Higher mechanical complexity: up to 4 linear actuators - Higher control complexity due to more DoF - More components → higher failure probability
C	- 3 contact points: locks rotation around EE axis - High adaptability: linear + rotational movement - Compact claws: no long stroke required - Potential reconfigurability for different shapes - Redundancy and modularity: independent finger control	- Most complex mechanically: mix of motors and actuators - Requires sophisticated control algorithms - Risk of mechanical interference between fingers - Motor reliability in space (vacuum, thermal cycles) can be critical

Table 4.17: Comparison of End Effector Solutions

Solution A stands out for its mechanical simplicity, relying on only one linear actuator. This leads to fewer components, making the system easier to model and control, and potentially more robust due to the reduced number of failure points. However, its two-point gripping mechanism allows unwanted rotation around the EE's central axis, compromising stability under dynamic conditions. Furthermore, the claw shape must match the target precisely, reducing adaptability and versatility, and finally the lack of redundancy means that failure of the single actuator

results in complete system failure.
Solution B presents a higher mechanical stability by implementing a three-point contact, which effectively prevents rotation around the EE axis. It uses simpler claw geometries that adapt to the target via linear movement, and the presence of multiple actuators introduces redundancy—enhancing grip reliability even in case of partial failure. This design also offers better adaptability to structures like rings due to its distributed contact and moving elements. On the downside, B introduces significantly higher mechanical and control complexity, employing up to four linear actuators and increasing the system's degrees of freedom. The rise in the number of components also raises the risk of failure and complicates the design.
Solution C also presents high adaptability by combining linear and rotational motion in its claws. Like B, it uses three contact points to ensure rotational stability, but it also allows reconfigurability and independent finger control, enabling it to handle a broader variety of target shapes. Its compact design eliminates the need for long strokes, improving spatial efficiency. The modularity built into Solution C provides redundancy and allows individual fingers to continue operating even if one fails. However, these advantages come at the cost of the highest mechanical complexity among the three. It integrates both motors and actuators, demanding sophisticated control strategies and introducing risks such as mechanical interference between fingers. Additionally, the reliance on motors presents challenges in space environments, where vacuum conditions and extreme temperature cycles can significantly affect performance and reliability.
Overall, each solution is optimized for a different set of mission priorities. Solution A is best suited for scenarios where simplicity, robustness, and low resource consumption are paramount. Solution B balances adaptability with moderate complexity, making it suitable for gripping known, moderately variable geometries with higher fault tolerance. Solution C offers the most flexibility and advanced capabilities but requires careful consideration of complexity and reliability in harsh environments. The selection ultimately depends on the trade-offs acceptable within the mission's operational and technical constraints. Such trade-offs are assessed in later phases of the project, to select the best solution and further detail its design.

Chapter 5

Conclusions

This thesis presented the early development of the ARCap Module, a plug-and-play payload designed to support the platform during Rendezvous and to perform Docking and On-Orbit Servicing.
The work covered the definition of a detailed Concept of Operations (CONOPS), an initial analysis of the launch vibration environment for launcher compatibility, and a preliminary end-effector design based on mechanical interface constraints derived from the Launcher Adapter Ring (LAR).
Through mission analysis, all phases of the module's operational lifetime were identified, along with its key functionalities, such as target search, tracking, capture, and servicing.
Following this, a vibration analysis was performed to assess the launch environment of the most commonly used launchers worldwide. In particular, a worst-case scenario was identified and used to derive the structural vibration requirements that the module must withstand during launch.
Furthermore, an in-depth analysis of the Launcher Adapter Ring was performed to determine interface constraints by evaluating both the largest and smallest envelopes resulting from the superposition of LARs used across multiple launchers. This supported the preliminary design of a capture mechanism optimized for adaptability, robustness, and compliance with integration constraints.
By establishing the design baseline and mission framework, this work contributes to the development of more sustainable and reusable on-orbit infrastructure. It also demonstrates the importance of early-phase analysis in reducing risk in complex space servicing missions.
Future work will involve the detailed development of subsystems, refinement of the structural analysis through static and dynamic load requirement identification and testing, and eventual integration and validation of the complete ARCap module on a host platform.

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