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How a dedicated refueling system can support a high-power electric spacecraft for Moon-Mars cargo transfers

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List of Acronyms

AOCS	Attitude and Orbit Control Subsystem
ConOps	Concept of Operations
CP	Chemical Propulsion
DMS	Data Management Subsystem
DRA	Design Reference Architecture
DRM	Design Reference Mission
EOL	End-of-Life
EOR	Electric Orbit Raising
EP	Electric Propulsion
EPS	Electrical Power Subsystem
FoM	Figure of Merit
HARN	Harness Subsystem
HET	Hall-Effect Thruster
I/F	Interface
ICV	Interplanetary Cargo Vehicle
LEO	Low Earth Orbit
LEOP	Launch and Early Orbit Phase
LOP-G	Lunar Orbital Platform-Gateway
MBC	Mars Base Camp

MDPS	Meteoroid/Debris Protection System
MMOD	Micrometeoroids and Orbital Debris
MoO	Mode of Operations
MOS	Mars Orbital Station
MTV	Mars Transfer Vehicle
NEAs	Near-Earth Asteroids
OBC	On-Board Computer
PBD	Phases Block Diagram
PCDU	Power Conditioning and Distribution Unit
PPE	Power and Propulsion Element
PPU	Power Processing Unit
PROP	Propulsion Subsystem
REF	Refueling Subsystem
RIU	Remote Interface Unit
S&M	Structures and Mechanisms Subsystem
SEP	Solar Electric Propulsion
TBD	To be defined
TCS	Thermal Control Subsystem
TT&C	Tracking Telemetry and Command Subsystem

Abstract

The thesis work deals with the analysis of Moon-Mars cargo transfers scenarios with the aim of supporting a future Mars orbital station. The presence of a Mars outpost poses the issue of its maintenance and sustainment: for these purposes, an electric space tug could be involved in cargo transportation missions. The scenarios describe the transfer of a multi-tons Cargo Module from the Near-Rectilinear Halo Orbit to 1-sol Mars Orbit, and vice versa. To support multiple transfers, dedicated refueling operations at a dedicated Orbital Refueling System are envisaged. The thesis work starts from an overview of the possible transportation mission concepts exploiting high-power solar electric propulsion; a brief system and mission analysis methodology is introduced. Then it focuses on the detailed definition of the mission objectives and constraints, and on the functional analyses at various levels. The most important results of these analyses are the functional architecture and the physical block diagram. The thesis work continues with the description of the Concept of Operations, from the mission phases analyses to the Modes of Operations definition, through an iterative refinement process. The overall mission scenarios have been derived from trade-off analyses that have been performed to choose the mission architecture that, most of all, cost-effectively satisfy stakeholder expectations. The most important features of these analyses and their results are described within the study. Eventually, in the last part of the study main conclusions are drawn on the selected mission scenarios.

Chapter 1

Transportation Mission Concepts exploiting Solar Electric Propulsion

1.1 Introduction

Sustainable access to space is necessary to advance human exploration capabilities. There is therefore a growing interest in the development of innovative transportation vehicles, that could implement an efficient and cost-effective method of transporting mass in space. The sustained exploration of the Solar system, including ambitious projects aimed at Moon and Mars, requires advances in multiple areas spanning nearly every aspect of space technology.

Among these technologies, Solar Electric Propulsion (SEP) is of particular interest because it offers higher specific impulse compared to the chemical propulsion and consequently higher propellant efficiency [26]. For this reason, despite not producing enough thrust to leave the Earth's atmosphere, it represents an ideal propulsion technology once on-orbit, especially for unmanned missions where travel time is less critical.

Several high-power SEP concepts are being developed to show how electric thrusters could be used for near-Earth applications and scaled up for ambitious deep space missions, providing significant fuel saving in comparison with conventional chemical propulsion. Among these concepts, the lower power ones represent missions that could be currently implemented to gain experience with these kinds of vehicles, whereas the higher power concepts help to envision how the technologies could scale to enable future capabilities.

1.2 Near-Earth Transportation Mission Concepts

In near-Earth missions electric propulsion could be conveniently implemented on servicing vehicles, envisioned to provide various services on-orbit, like orbital payload transfer, end-of-life satellites disposal and space debris removal, on-orbit assembly and life extension refueling. The electric thruster power required in these kinds of missions could approximately span a power range of tens of kW .

EPS could be implemented in a reusable and versatile electric space tug for Earth satellites servicing. An electric space tug could be exploited in support of satellites transfer maneuvers from Low Earth Orbit (LEO) to higher operational orbit. In this scenario the pre-deployed tug is supposed to actively perform rendezvous and docking with the satellite, which has been released by the launcher in a non-definitive low orbit, and to bring and release it to the expected operational orbit [8]. Thus, the satellite would not need to perform the final transfer to its operational orbit: this allows reducing the propulsion on the satellite, in favor of a greater payload mass capability.

A similar system could be used for removal of space debris from near-Earth orbits. Nowadays, there is a growing interest to provide active debris removal to reduce the potentially dangerous objects, such as inactive satellites and launcher upper stages, accumulated over 50 years of space activities [7]. The new international standards, shared by the main space agencies, put a limit on the accumulation of masses in space. They require either the de-orbiting of an inactive satellite in no more than 25 years (if the satellite is in LEO) or a disposal maneuver for the re-entry or the positioning in a graveyard orbit (for satellites in geostationary orbits or in medium Earth orbits).

If coupled with a reusable re-entry vehicle, the electric space tug system could support the retrieval of significant payload samples on Earth: in this case the two systems would rendezvous in a defined orbit in order to move the payload sample from the space tug to the re-entry vehicle and return it back to Earth [8].

1.3 Cislunar Transportation Mission Concepts

The cislunar environment represents the proving ground to test and demonstrate the systems on which long-duration missions into deep space shall rely. In fact, cislunar environment provide conditions similar to that encountered in deep space. Significant work is required to mature technologies before embarking on missions that are independent of Earth. The cislunar flight testing is therefore a necessary step to enable the use of high power SEP for deep space transportation

missions.

According with the NASA’s approach to the exploration beyond LEO, the focus of lunar vicinity phase is the assembly of the Lunar Orbital Platform-Gateway (LOP-G), a planned lunar-orbit space station, whose power and propulsion capabilities would be provided by the Power and Propulsion Element (PPE), a $40kW$ SEP system augmented with a chemical reaction control system.

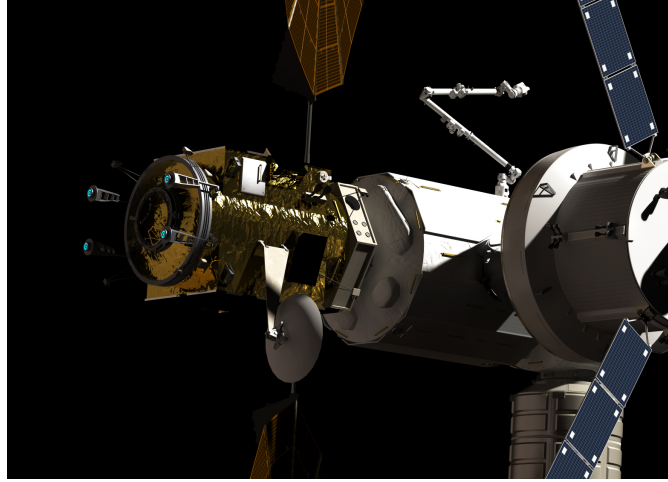


Figure 1.1: A model of the PPE (left) at the LOP-G

The PPE would be in charge of maneuvering and transferring the LOP-G between various orbits to support different types of missions [3]. It is expected to be around an order of magnitude more powerful than the propulsion system used on missions like Dawn and, since Mars transportation systems may need to be another order of magnitude more powerful, it represents a good intermediate testing platform. The PPE is conceived to incorporate a lot of the technologies NASA was developing for the Asteroid Redirect Mission (ARM), now cancelled.

ARM concept was that of using SEP to redirect a large amount of asteroidal mass to a lunar orbit where crew could have collected and analyzed samples without requiring long-duration human transport [18, 19]. The asteroidal mass could have been an entire asteroid or a boulder extracted and a $40kW$ SEP system was envisioned to accomplish the objective. Beyond testing an advanced SEP system and demonstrating planetary defense technique, ARM goal was that of providing a high-value target in cislunar space, that would have required a human presence to take full advantage of this new resource.

Moreover, the presence of a lunar outpost poses the issue of its maintenance and sustainment: for these purposes, an electric space tug could be involved, especially when unmanned and logistics transportation missions are considered

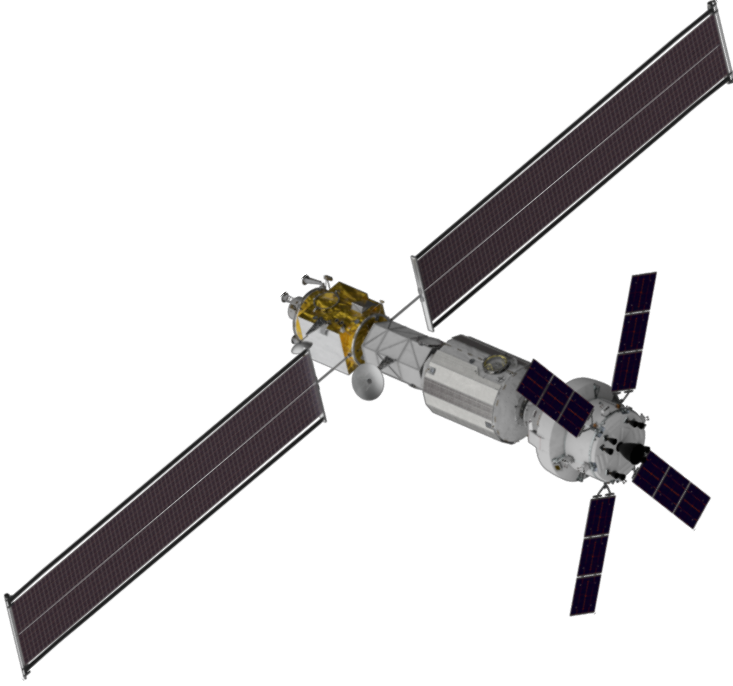


Figure 1.2: A LOP-G conceptual construction; PPE is shown on the left side

[13, 14, 17]. In this scenario the transfer time is less critical than in ones in which the human factor is involved. This kind of missions includes the delivery of logistics and supplies to maintain and resupply the station as well as the transfer of infrastructures for its growth and development.

1.4 Deep Space Transportation Mission Concepts

The cislunar space represents the next step in the human space exploration pathway, but the progressive expansion of human capabilities calls for Mars and other deep space destinations. Experience and knowledge gained while operating in the lunar vicinity would be necessary when facing with challenging missions to

farther targets.

NASA's Evolvable Mars Campaign investigates a split architecture that employs SEP to pre-place cargo to Mars and chemical propulsion to transfer the crew: while the high efficiency of a SEP system is ideal for delivering cargo to Mars, long trip times associated with low-thrust trajectories are undesirable for crew health and safety. This split architecture draws on the strengths of each technology to perform two complementary functions required for Mars human exploration. In this concept a SEP system, providing $150kW$ of electric thruster power, will be necessary to deliver on a Mars orbit elements such as habitats, orbital maneuvering systems, consumables, and landers for use in the Mars environment, including Phobos and Deimos environments [19].

Lockheed Martin's Mars Base Camp concept also involves SEP to pre-deploy assets in Mars orbit and haul items to cislunar space, where they would be assembled and tested before going to Mars. In particular in this concept the $200kW$ class SEP would be in charge of pre-place the Phobos/Deimos excursion system, the laboratory and science equipment, the center node and certain consumables that are not required for survival [5, 6]. Also in this case less time critical cargo delivery is, therefore, entrusted to electric propulsion.

Before preparing human missions in vicinity of Mars, however, an important milestone would be a robotic Mars sample return mission, which could represent a good candidate to exploit SEP. High scientific value would derive from the analysis of the sample, nevertheless, many new technologies would be required to carry out this pioneering mission: a landing system, an ascent vehicle, a rendezvous system in Mars orbit and an Earth re-entry vehicle.

Other ambitious objectives are Near-Earth Asteroids (NEAs). In this frame a NASA's study investigated the use of SEP to transport crew directly to a NEA [19]. In fact, small body rendezvous missions such as NEAs missions are expected to receive significant benefits in term of cost savings when SEP is used. It is no coincidence that missions Deep Space 1, Hayabusa and Dawn, all of them using SEP, have visited small bodies. A NASA's SEP concept for human exploration of NEAs consists of a mission in which a SEP stage together with a space habitat and an excursion vehicle rendezvous with the Multi-Purpose Crew Vehicle and a chemical stage. After the Earth-departure burn provided by the chemical stage, the rest of the heliocentric transfer to and the rendezvous with the NEA is performed by the SEP stage, as well as the return trip of the crew vehicle to Earth orbit.

In the region of the Inner Solar system Venus and Mercury have always been of extreme interest and our knowledge of them is far from being completed. Currently BepiColombo, an exploration mission to Mercury, has been planned, carried out jointly by the European Space Agency (ESA) and the Japan Aerospace Exploration

Agency (JAXA) [2]. Two spacecrafts will be launched together and in a stacked configuration with the propulsion element, the Mercury Transfer Module (MTM). From their operative orbits two spacecrafts, the Mercury Planetary Orbiter (MPO) and the Mercury Magnetosphere Orbiter (MMO) will study the planet and its environment. The major part of the ΔV required during cruise is provided by the SEP system of the MTM, while a bi-propellant propulsion system is used for attitude control.

Scientific/robotic missions towards outer planets of the Solar System are the long-term exploration opportunities that would be opened by next SEP generations. The long-duration, high-efficiency operations of SEP systems enable mission that can be difficult and expensive to design implementing a propulsion system based on chemical propulsion. Possible targets identified are the moons of Jupiter and Saturn, Uranus and Neptune to search for evidence of life.

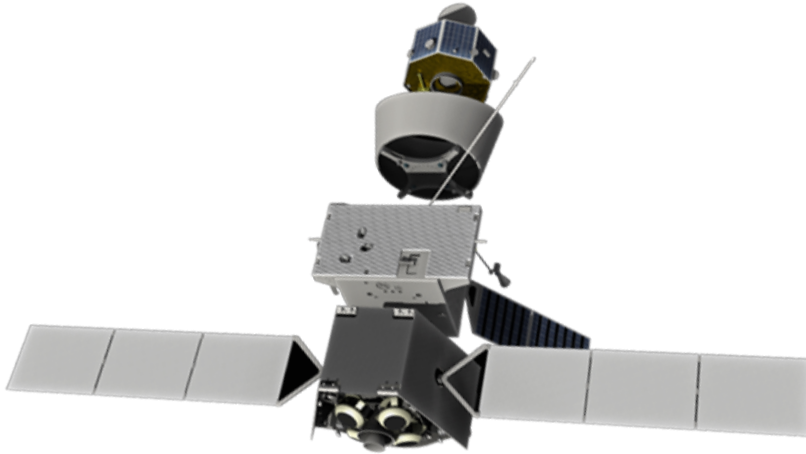


Figure 1.3: BepiColombo elements; from the bottom up: the MTM, the MPO and the MMO

1.5 The Moon-Mars Transportation Mission Concept

The analysis of transportation mission scenarios, exploiting high power electric propulsion, between Moon and Mars is the scope of this study. The root problem is the realization of cargo transfer between the LOP-G referred to in paragraph 1.3 and an orbital station around Mars. The mission aims to link these two architectures to support cis-Martian space exploration through the delivery, from the lunar environment, of assets and supplies necessary to sustain the Mars-orbiting outpost and its operations. A general overview is given for both station concepts.

1.5.1 The LOP-G Concept

NASA has planned to place the habitable spacecraft LOP-G at the Near-Rectilinear Halo Orbit (NRHO). As referred to in paragraph 1.3, LOP-G will include the Power and Propulsion Element (PPE), the advanced SEP service module developed thanks to a public-private partnership, that will provide both orbital maintenance and transfer between lunar orbits. Other fundamental elements will be a habitation element, a logistic element and an airlock, which, together with the visiting Orion spacecraft, will constitute the habitable elements of the station. These main elements will enable a crew of four members to live and work in cislunar space for at least 30 days.

Feasibility trades and future works will determine which additional elements will extend the platform capabilities. They could be partner-provided elements to support science and technology activities, as well as lunar landers to enable missions to the lunar surface. They could include also elements for the assembly of the Deep Space Transport (DST), a crewed interplanetary spacecraft concept to support science exploration missions to Mars of up to 1000 days. The DST is envisioned to depart from the LOP-G and return there, in order to be refueled and reused.

Scientific operations and opportunities at the LOP-G and other possible activities will aim to demonstrate many capabilities that will be needed for deep space mission including telerobotics and sample return. LOP-G could also have an important role in staging human missions to the lunar surface. In this case LOP-G additional functions will be required, such as providing storage and refueling of a reusable ascent module and providing safe haven for crew aborting from the surface.

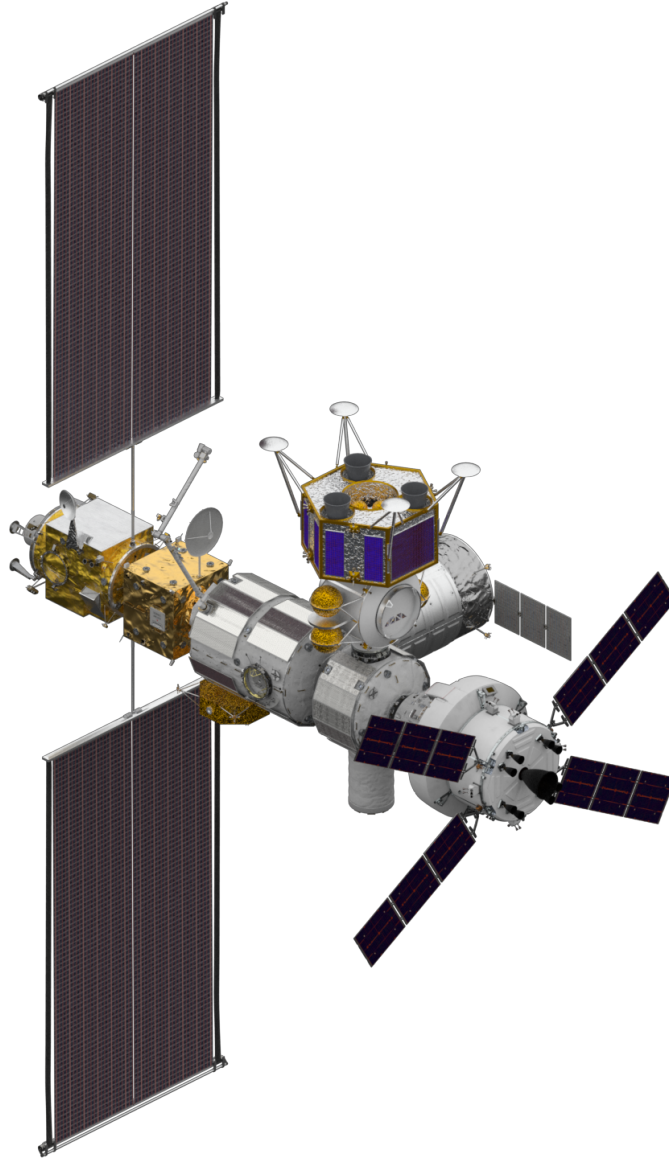


Figure 1.4: A LOP-G conceptual construction with the added lander to enable lunar surface mission scenarios

1.5.2 The Mars Orbital Station Concept

Many mission concepts for expeditions to Mars were proposed in the late decades and in most cases an orbiting station around Mars is the core element. This allows close observation of the Red Planet and provide a platform for exploration of the Mars environment and surface. In the analysis proposed in this study

the orbital outpost at Mars is referred to as “Mars Orbital Station” and abbreviated as “MOS”. Its characteristics are assumed to be the most widespread among that of some remarkable proposal until now envisioned in the frame of manned missions to Mars. A comparison between different concept is shown in Table 1.1, which contains the overall mission highlights for every concept. Subject of this comparison are:

- The Human Exploration of Mars Design Reference Architecture 5.0 (DRA 5.0), released by NASA in 2009 [10];
- Project M^3 , a study for a manned Mars mission in 2031, developed during the Space Summer School in Alpbach in 2003 [24];
- Mars Base Camp, an architecture for sending human to Mars presented in 2016 by the American company Lockheed Martin [5, 6];
- The Interplanetary Expedition Complex (MEK), a Russian concept for an orbital human mission to Mars developed and designed by the Russian manufacturer RKK Energia [9];

In M^3 , MBC and MEK concepts, an orbital station around Mars is conceived as a close-up outpost from which short-duration surface missions, involving only part of the crew, can be carried out through the exploitation of ascent-descent vehicles. In DRA 5.0, instead, the mission is a long-duration surface mission involving all the crew. Once arrived in Mars orbit aboard the Mars transfer vehicle (MTV), the crew perform a rendezvous with the surface habitat, previously deployed, which would serve as the transportation vehicle to the surface, while the MTV remains in orbit, waiting for the crew return. In the table MTV features are considered for the DRA 5.0 column.

In view of these considerations, we assume the Mars Orbital Station as an orbital station in a 1-sol orbit around Mars with a crew of six confined in 500 m^3 of pressurized volume. It is conceived for a total mission of three years, exploiting Nuclear Thermal Rocket (NTR) propulsion for in-space transfer and solar arrays for electric power generation. For its assembly, each module which composes the multi-modular station will be launched in a High Earth Orbit. The final total mass of the station will be between 500 and 700 tons including the ascent-descent module envisioned for short-duration surface missions involving only part of the crew.

In the following chapters, the Mission Analysis performed by a high-power electric space tug in a cargo transfer scenario between the LOP-G and a generic Mars habitat, referred to as Mars Orbital Station (MOS), is described

	DRA 5.0	M ³	MBC	MEK
Mission Length (yrs)	~6	~3	~3	~2
Mars Orbit (km)	1-sol (250 x 33,793)	~350	1-sol (250 x 33,793)	1-sol (250 x 33,793)
Martian Orbit Stay (months)	-	~18	~11	~1
Surface Stay (months)	~18	~0.5	~0.5	~0.5
Propulsion Type	Nuclear Thermal Rocket (NTR)	Bimodal Nuclear Thermal	Cryogenic	Solar Electric
Power Generation	Solar Electric	Bimodal Nuclear Thermal	Solar Electric	Solar Electric
I _{sp} (s)	900	1000	440	3970 (Ion Thrusters)
Crew Size	6	6	6	6
Mass to LEO (t)	~356 (MTV)	~756	~726	~510
Pressurized Volume (m ³)	~342 (MTV)	~825	~720	~410
ISRU	yes	no	no	no

Table 1.1: Data comparison for the different Mars mission concepts

In Chapter 2, an overview of the analysis methodology adopted is presented and the tools used for system definition and mission definition are specified. The Mission Statement and the Primary and Secondary Objectives are presented and described in Chapter 3. Chapter 4 goes deeper in the system definition at both system and subsystem level. In Chapter 5 different mission scenarios are identified and mission analysis is presented for two of them. In Chapter 6 a trade-off analysis is carried out to identify which is the best scenario between those considered.

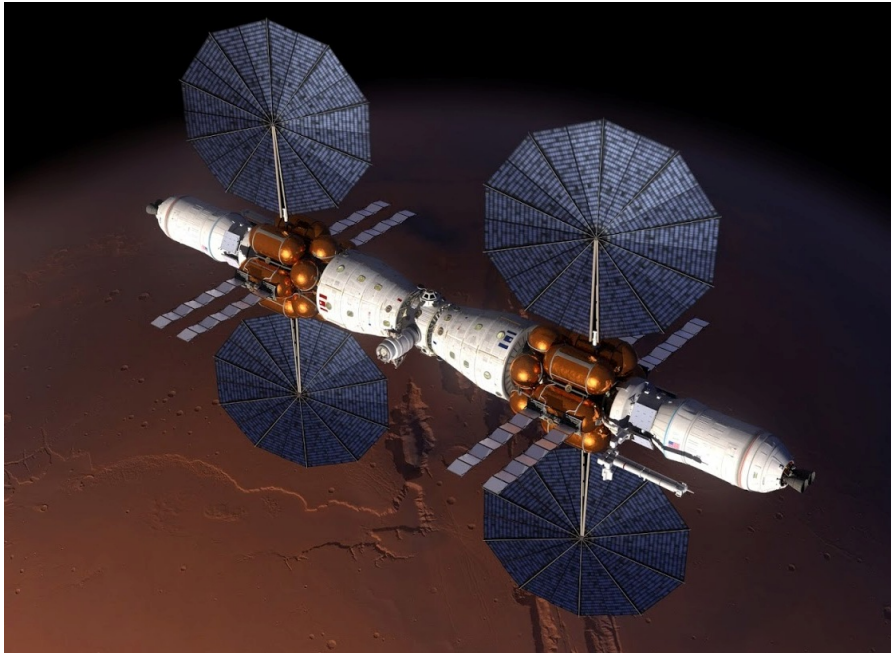


Figure 1.5: Mars Base Camp configuration in Mars orbit



Figure 1.6: MTV "In-Line Configuration" in LEO prior to departure

Chapter 2

System and Mission Analysis Methodology

2.1 Analysis Process

The approach to complex problems, from the system engineering point of view, follows an iterative and recursive procedure, in which the application of processes is repeated to define ever lower layer of the system composition, allowing to go deeper in detail in the analysis of its configuration [25]. Typically steps of this process are schematically illustrated in 2.1. These steps allow a continue refinement of requirements, leading to a more thorough system definition.

The very first step is the definition of the Mission Statement, a clear and concise declaration of mission purpose for existence, which is at the basis of the mission concept. It shall qualitatively identify the goals of the mission and the drawback results obtained from it.

Once the Mission Statement has been drawn, the mission objectives and constraints are derived. They drive the analysis and the design of the whole mission. The Primary Mission Objectives, specifically, can be directly derived from the Mission Statement, while additional objectives, called Secondary Mission Objectives, can be determine through the Stakeholders Analysis. This analysis is usually subdivided in two consecutive steps: firstly, it is necessary to identify all the stakeholders, i.e. all the main actors involved in the mission, secondly, it is necessary to determine their needs and expectations. Mission Constraints are other crucial issues that impose some limitations to the mission analysis and design.

The Mission Statement, Objectives and Constraints shall be fixed early because they represent the mission foundation. For this reason they cannot be modified or

re-adapted during the following iterations. After their setting, the essence of the analysis process can be split in two main branches: the Functional Analysis and the Concept of Operations, which aim at a better characterization of the systems involved in the mission, and the mission operations, respectively.

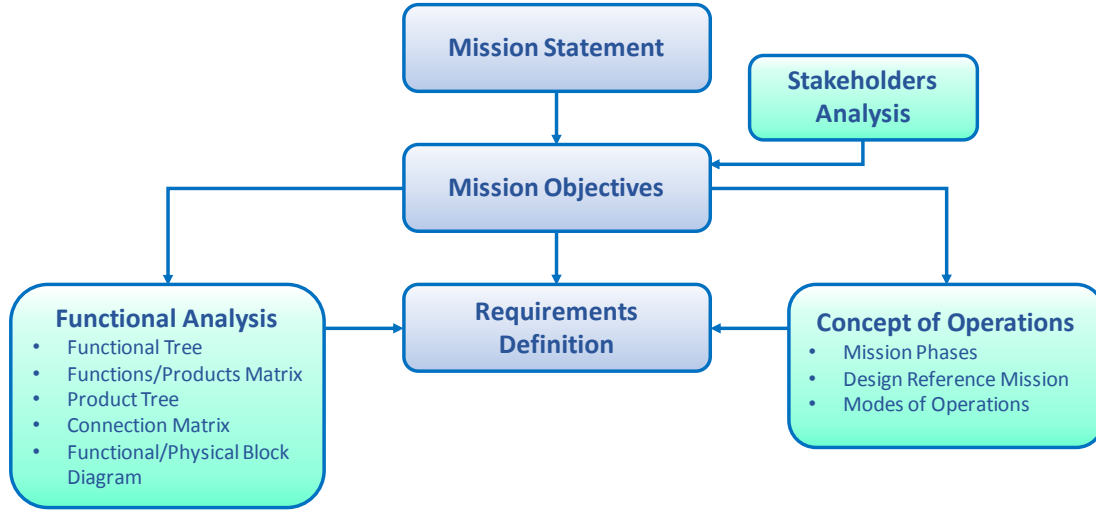


Figure 2.1: General methodology overview

2.2 Functional Analysis

Functional Analysis is a fundamental tool of the analysis process to investigate a new concept and determine its architecture from the functional point of view. The Functional Analysis is a recursive process, meaning that it shall be repeated starting from the highest level (System of Systems) to the successive lower layers (System, Subsystem, Equipment, etc.). Once applied to the various levels, it allows defining the functional architectures of the System of Systems, the System and the Subsystem layers.

For sake of clarity, we can think that the functional System of Systems architecture is completed when all its elements, i.e. the Systems, have been identified and their relations determined. Analogously, the elements of the System architecture are the Subsystems while in the Subsystems architecture they are the Equipment. This product breakdown is useful to gradually refine the requirements that shall have to be satisfied to fulfill the mission.

The steps to be accomplished in order to carry out the Functional Analysis are:

- Functional Tree;
- Functions/Products Matrix;
- Product Tree;
- Connection Matrix;
- Functional/Physical Block Diagram;

Figure 2.2 shows the flow-chart of the proposed Functional Analysis, illustrating all its steps and their sequence.

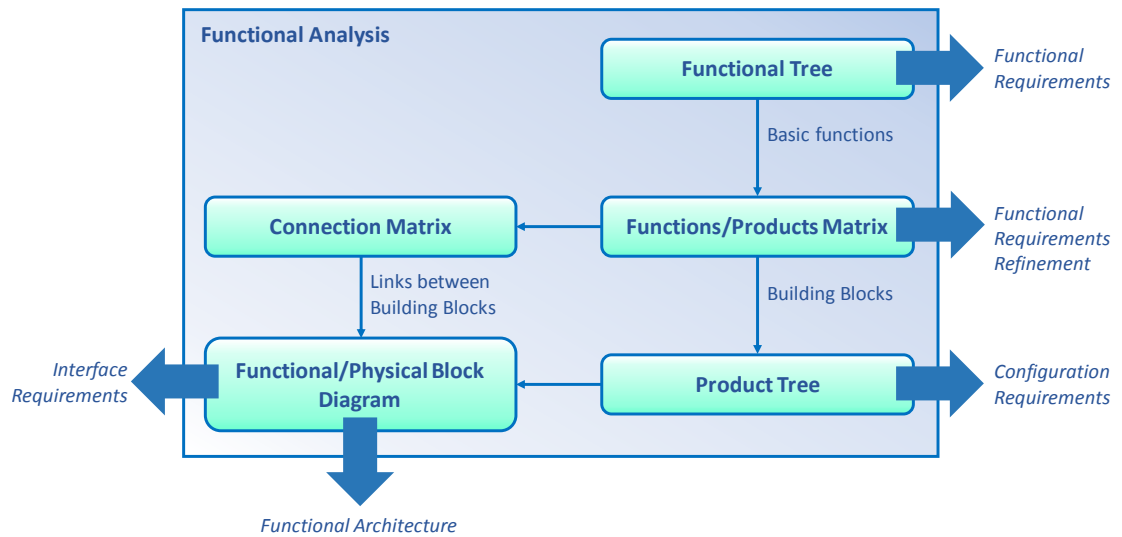


Figure 2.2: Functional Analysis flow-chart

A primary result of the Functional Analysis is the **Functional Tree**, which allows splitting the higher level functions, deriving from mission objectives and constraints, into lower level ones. The aim is to identify the basic functions that have to be performed. Higher level functions represent complex tasks that need to be decomposed into ever simpler ones, until basic functions are detected. These are at the bottom of the tree and cannot be split any further. The lower level functions can be obtained from the higher level ones by asking "how" that higher level function can be performed. Conversely, from higher level we can move to lower level by asking "why" that function has to be performed. Figure 2.3 clarifies this process.

For the System of Systems level, the basic functions are those corresponding to Systems task, they stay at the bottom of the System of Systems Functional Tree, but are at the top of the Functional Tree at System level. Similarly, for the System level, the basic functions are those corresponding to Subsystems tasks and which stay at the top of the Functional Tree at Subsystem level. Eventually, for the Subsystem level, basic functions are related to Equipment functions.

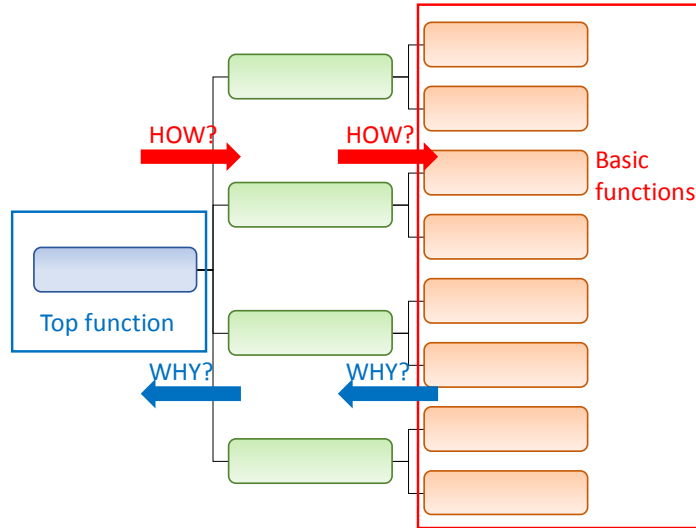


Figure 2.3: Functional Tree

After identifying the basic functions for the level considered, we need to choose the elements that will perform those functions. This is obtained by means of the **Functions/Products Matrix**, which allows us to match the basic functions to the relative elements able to perform them. Basic functions are written in the rows of the matrix while products will be in the columns. Simply asking ourselves which element is able to perform the function under consideration, we can add a new column containing the corresponding element, if not yet identified, and tick their intersection. Eventually all necessary products are determined. They represent the so-called “Building Blocks”, i.e. the elements constituting the functional architecture for the level under consideration.

As third step, the Product Tree is generated by grouping the Building Blocks. Figure 2.4 gives evidence of these processes. Depending on whether the level considered is Subsystem, System or System of Systems, the Building Blocks will be respectively Equipment, Subsystems or Systems. When the Building Blocks are Systems, for example, they may be grouped into segments to form the Product Tree of the System of Systems.

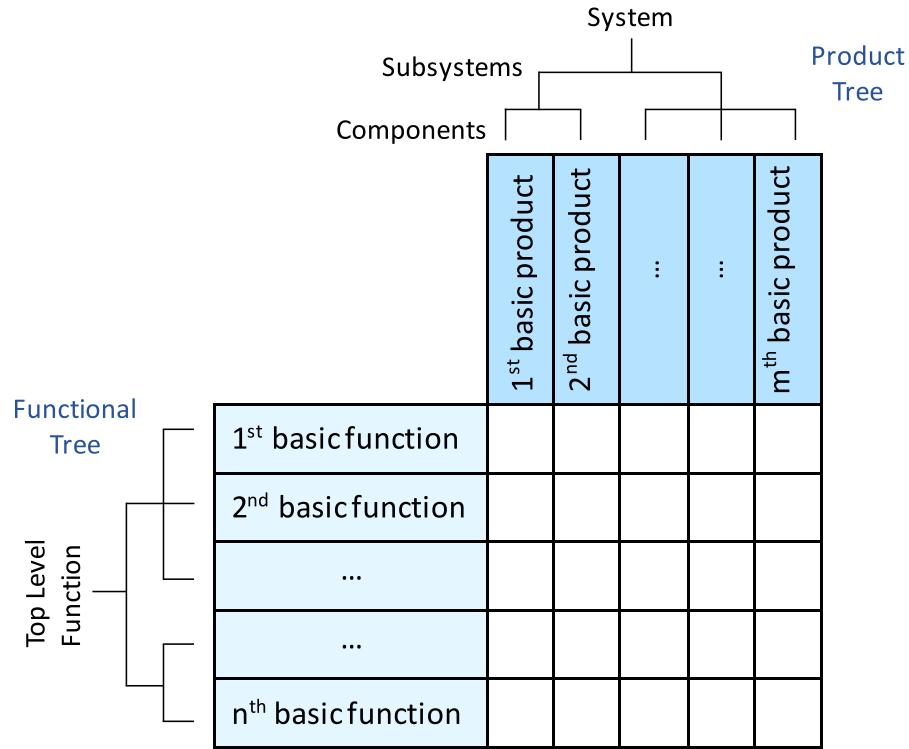


Figure 2.4: Functions/Products Matrix in relation to Product Tree and Functional Tree

Once the Building Blocks have been identified, the next step is to make evidence of their interconnections by means of the **Connection Matrix**. In this matrix both rows and columns contain the Building Blocks and the intersection between two elements is ticked when a connection between them is identified. Information about the nature and the directionality of the connections are not yet given. To provide them, a further step is necessary: the **Functional/Physical Block Diagram**, in which the Building Blocks are linked through arrows that highlights where the connections are pointing to, and what kind of links they are, if electrical, mechanical or data link, etc. Both steps are schematically represented in Figure 2.5.

After developing the Connection Matrix and the Functional/Physical Block Diagram, the functional architecture for the level concerned is broadly determined and the relationships between the various components clearly identified.

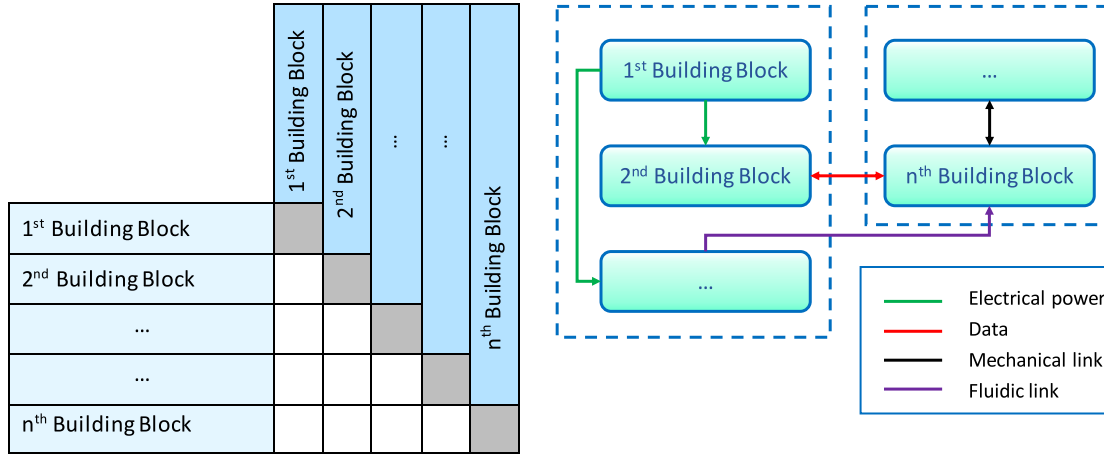


Figure 2.5: Connection Matrix and Functional/Physical Block Diagram

2.3 Concept of Operations

The Concept of Operations (ConOps) is a description of how the system will be operated during the mission in order to meet stakeholders' expectations. It is an important step in mission analysis because it provides an operational perspective, allowing the derivation of requirements more specifically related to the use of the system. The operational point of view of the system, assessed through the ConOps analysis, often allows the designers to reveal system functions that have not been considered before. Furthermore, ConOps serves as the basis for specific operational documents that should be defined later during the mission planning.

The definition of the ConOps is also an iterative process that has to be performed until the desired level of detail. The ConOps can include many aspects of operations, such as: Mission Phases, Modes of Operation, Mission Timelines, Design Reference Missions (DRMs) and/or Operational Scenarios, End-to-end Communication Strategy and/or Command and Data Architecture, Operational Facilities, Integrated Logistic Support (i.e. resupply, maintenance and assembly information) and Critical Events. Among these tools, the ones chosen for the ConOps development in the present study are:

- Mission Phases
- DRMs
- Modes of Operations

In the **Mission Phases** the major phases of the mission are time-sequentially

described. To properly delineate the phases, it's important to consider the various external environments, both natural and induced, in which the system has to operate, in terms of loads, temperatures, pressure, radiation and other critical environmental factors. Each environment defines the general state of the system operating in those specific conditions and, therefore, characterizes a different mission phase. This characterization has to be done for the full system life-cycle, from the deployment to the disposal.

The **DRM** provides a visual representation of the mission phases and their sequence. It shows the Building Blocks involved in the various phases and in which orbits they are. Figure 2.6 provides an example of a DRM from our study, this would be fully explained in Chapter 5.

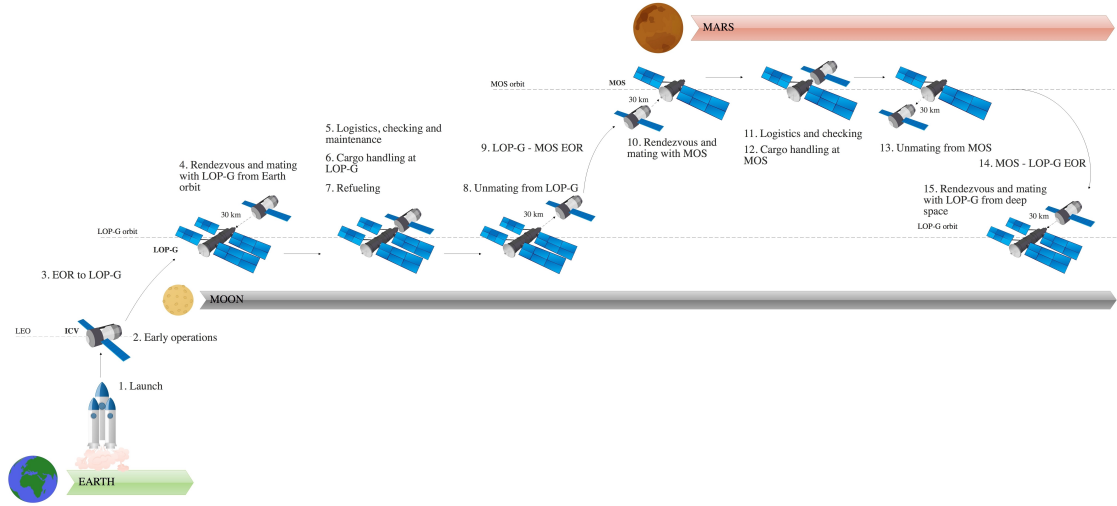


Figure 2.6: An example of Design Reference Mission

During each mission phase, the system can enter in various **Modes of Operations**. A Mode of Operation is an operational state of the system determined by a precise definition of all subsystems and equipment that have to be activated or not in that specific mode. Table 2.1 is useful to describe all the possible modes that can be triggered by the system during the various mission phases. When the mode is accessible in a particular phase, their intersection is ticked. In addition to characterizing the Modes of Operations, it is also important to highlight which transitions between the different modes are possible and in which cases these transitions occur. Diagrams and tables like those shown in Figure 2.7 provide this kind of information, clarifying all possible transition events.

Phases \ Modes	Mode 1	Mode 2	Mode m
Phase 1	X				
Phase 2		X			X
...	X				
...			X		
Phase n	X			X	

Table 2.1: Mission Phases/Modes of Operations table

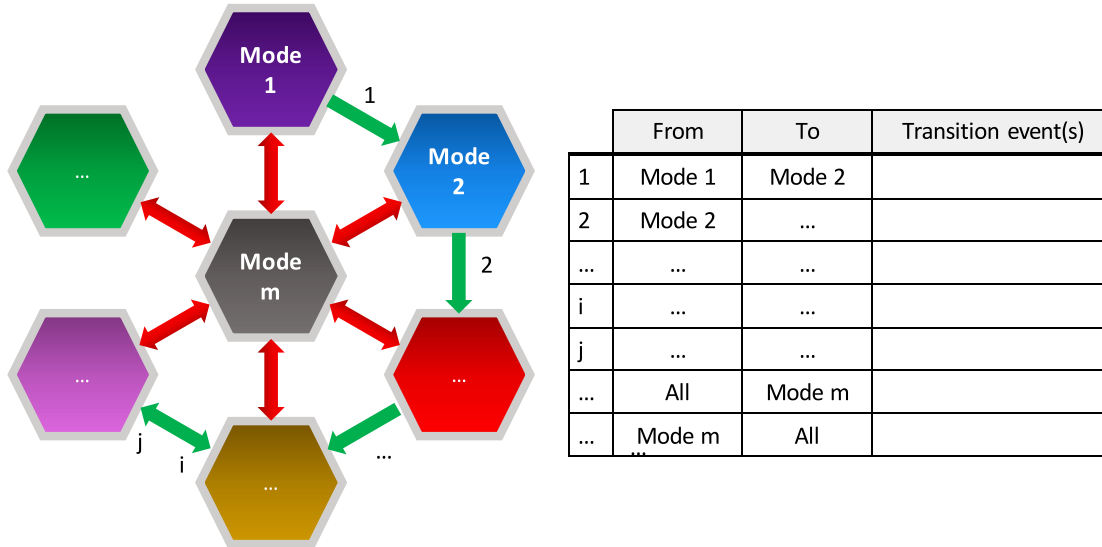


Figure 2.7: Modes of Operations transition diagram and table

2.4 Requirements Definition

We said in previous paragraphs that all the steps considered in the analysis process are important drivers for the requirements definition. But why are requirements so important and what they allow us to obtain? Requirements are brief and concise recommendations, describing which are the characteristics and the capabilities that the system should satisfy. In the requirements definition process the stakeholders' expectations are transformed into a complete set of validated

requirements expressed as “shall” statements, that must be unambiguous and verifiable. Keeping track of all derived requirements is extremely helpful, especially when submitting the design to the review phases, in order to understand if it is compliant to stakeholders’ expectations.

Through the proposed methodology different categories of requirements can be generated. The relations between these categories and the main tools of the methodology used to derive them are illustrated in Figure 2.8. They include:

- *Mission Requirements*: requirements related to a task, a function, a constraint, or an action induced by the mission scenario. They directly derive from Mission Statement and Mission Objectives and Constraints.
- *Programmatic Requirements*: other top-level requirements deriving from objectives and constraints imposed by the stakeholders, more related to schedule, cost and strategies.
- *Functional Requirements*: requirements that define what the product shall perform, in order to conform to the needs/Mission Statement or requirements of the users. They derive from the basic functions of the Functional Tree and are successively refined through the Functions/Products Matrix information.
- *Configuration Requirements*: requirements dealing with the product composition and its organization. They are deduced from both the Functions/Products Matrix and the Product Tree.
- *Interface Requirements*: requirements which specify the connections existing between the Building Blocks. They can be determined through the Connection Matrix and are subsequently refined with link type information through the Functional/Physical Block Diagram.
- *Environmental Requirements*: requirements related to the system environment during its life cycle; this includes the natural environments and induced environments. They can be derived from the Mission Phases analysis.
- *Operational Requirements*: requirements dealing with the system operability. They can be determined from the Modes of Operations analysis.

From the requirements listed above, additional categories of requirements can be derived. In this study will be provided some examples of *Performance Requirements*, which can be established from Functional Requirements. They describe quantitative features related to the functions expressed in the Functional Requirements.

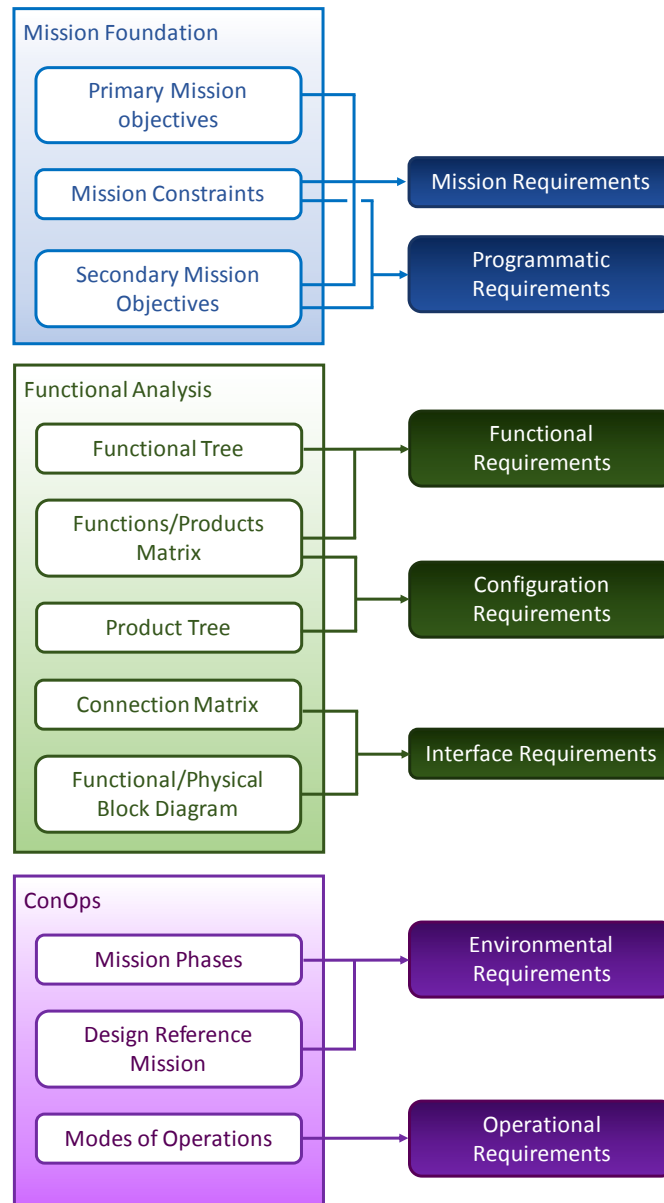


Figure 2.8: Requirements Definition Process

Chapter 3

Mission Objectives and Functional Analysis at System of Systems Level

3.1 Mission Basis

3.1.1 Mission Statement and Constraints

A set of questions can be used to properly drawn up the Mission Statement which represents the mission purpose, what the mission needs to achieve and why.

What is the root problem?

The root problem is the realization of cargo transfer between cislunar and Mars proximities. We aim to link these two environments to support cis-Martian space exploration through the delivery of supply, fuel, habitat modules, and other material necessary to sustain the Mars-orbiting outpost and to make it growth. A robust logistic strategy is therefore necessary to deliver assets provided via the Moon.

How can the issue be solved?

The issue can be solved by designing a system adopting high power electric propulsion, that shall provide cargo transfer between the two stations.

Are there other significant constraints imposed by top level scenario?

The system should be able to accomplish multiple end-to-end transfers: it is conceived as a reusable system and it should exploit existing infrastructures at LOP-G and MOS. Furthermore, to extent its serviceability to many scenarios as possible, the system shall be able to support the MOS in different phases of its operational lifetime.

In view of these considerations both the Mission Statement and Mission Constraints can be set down.

MISSION STATEMENT

In order to support cis-Martian space exploration, the mission will provide cargo transportation between the Lunar Orbital Platform-Gateway and the Mars Orbital Station, through an electric-propelled system able to transfer every resource necessary to sustain the Mars station infrastructure in its initial development, successive evolution, as well as in its operations and crew support.

Mission Constraints:

- The transportation system shall transfer end-to-end unmanned payloads exploiting existing infrastructures;
- The transportation system shall be conceived as a reusable space transportation system able to perform multiple transfers and on-orbit refueling operations;
- The transportation system shall provide support to the Mars Mission¹ during all phases of its extended mission timeframe.

Since space operations over the long term need to be sustainable to advance human exploration capabilities, the system is conceived as reusable. For the purposes of this study, reusability is the ability to use a system for multiple missions without the need for replacement of systems or subsystems. Only replenishment of consumable commodities, such as propellants, occurs between missions. Dedicated refueling operations shall, therefore, be envisaged.

3.1.2 Mission Objectives

As explained in paragraph 2.1 Primary Mission Objectives should come largely from the Mission Statement and represent the broad goals of the mission.

¹"Mars Mission" indicates the mission of exploring cis-Martian space by means of the MOS, this is the broader mission within the mission of the transportation system is intended to provide service.

Primary Mission Objectives:

- To support cis-Martian space exploration;
- To provide transportation system between LOP-G and MOS;
- To sustain development, evolution, operations and crew support of the Mars Orbital Station;
- To employ electric propulsion.

To properly derive Secondary Mission Objectives, it's necessary to carry through with the **Stakeholders Analysis**. Therefore, stakeholders shall first be identified and then their expectations shall be determined. Since the mission under consideration is not foreseen within the actual space context, we just provide a general overview of reasonable stakeholders for the main stakeholders' categories. These are:

- **Sponsors**, associations or private who set down mission statement, establish bounds on schedule and funds availability. Considering our mission they may be *National Space Agencies* of the current ISS and the future LOP-G participating countries and their Commercial Partners.
- **Operators**, people in charge of controlling and maintaining space and ground assets. They typically consist of engineering organization. In view of our mission, they may be *Private Space Companies*, which develop main technological features, *Private Suppliers*, which provide services and resources for certain portions of the system operations and *National Space Agencies*, which provide existing facilities.
- **End-users**, people that receive and use the space mission's products and capabilities. Considering that our mission is in support of the broader Mars Mission, in this case end-users may include the *National Space Agencies* of the current ISS and the future LOP-G participating countries and the *Scientific Community*, which would take advantage of the huge science return from exploring cis-Martian space.
- **Customers**, users who pay fees to use a specific mission's product. Reasonably, they may not be expected in the primary context of our mission, but we can think that, in a possible platform evolution, there might be interest from *Private Space Companies* in paying a fee to use the cargo vehicle for materials transportation.

Stakeholders' expectations and needs constitute the Secondary Mission Objectives. To fix them, we have considered which could be the crucial issues for the realization of our mission, that the stakeholders would need to stress.

Secondary Mission Objectives

- To standardize mating elements and interfaces for rendezvous and docking;
- To exploit existing ground and launch facilities necessary to support launch and orbital insertion;
- To exploit existing space facilities for on-orbit refueling;
- To deliver assets in compliance with schedule and needs identified in the various scenarios;
- To allow highly autonomous unmanned in-space operations;

From the Mission Statement and Mission Objectives and Constraints, *Mission Requirements* and *Programmatic Requirements* have been derived. They are listed in Appendix A.

As the mission has been identified, we assign it a name and a logo. Thus, in following chapters the considered system is referred to as "Interplanetary Cargo Vehicle" or "ICV" and its mission is "The ICV mission".



Figure 3.1: Mission logo

3.2 Functional Analysis at System of Systems Level

3.2.1 Segments Identification

To provide the starting point for the Functional Tree we need to identify a top level function deriving from the Mission Objective and Constraints that could represent the primary, broad, complex function for the mission to be performed. We have expressed it as: *To perform multiple end-to-end cargo transfers between lunar and mars proximities*. This can be split in four main high level functions, as indicated in Figure 3.2 :

1. To provide launch capabilities;
2. To provide transportation capabilities;
3. To provide mission support capabilities from orbit;
4. To provide mission support capabilities from Earth.

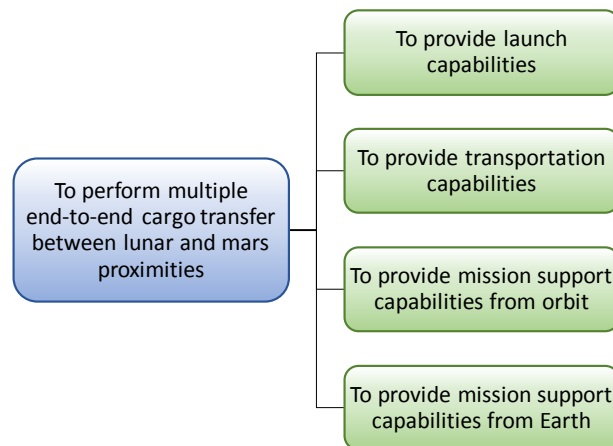


Figure 3.2: Top Level Functional Tree

From these four main functions early functional requirements can be generated. They are "shall" statement expressing the tasks indicated in the functions.

Functional Requirements

- Launch capabilities shall be provided;
- Transportation capabilities shall be provided;

- Mission support from orbit shall be provided;
- Mission support from Earth shall be provided.

The four main functions are to be ascribed to the Mission Segments through the Functions/Products Matrix illustrated in Figure 3.3 on the left side. The Launch

		SoS Segments		
		Launch Segment	Space Segment	Ground Segment
Functions	To provide launch capabilities	X		
	To provide transportation capabilities		X	
	To provide mission support capabilities from orbit		X	
	To provide mission support capabilities from Earth			X

	Launch Segment	Space Segment	Ground Segment
Launch Segment			
Space Segment	X		
Ground Segment	X	X	

Figure 3.3: Functions/Products Matrix (left) and Connection Matrix (right) - Segments Level

Segment include systems and facilities necessary to perform launch, the Space Segments is related to on-orbit mission elements, while the Ground Segment consists of all the ground-based control facilities. Understandably, they are all interconnected, as shown in the Connection Matrix on the right side of Figure 3.3 .

3.2.2 Systems Identification

To define the elements being part of the functional architecture at System of Systems Level, it is necessary to extent the Functional Tree until it is possible to identify functions related to specific systems. The basic functions for the System of Systems Level are shown in Figure 3.4 at the bottom of the Functional Tree.

Since reusability is included in mission objectives, specific functions related to refueling operations have to be taken into account when splitting the *To provide mission support capabilities from orbit* function into lower-level functions. It should also be considered that, in a more crowded space, space assets providing coordinates necessary to enhance autonomous navigation are to foreseen. Navigation capabilities should, therefore, be provided both in cislunar proximity and in mars proximity. Another fundamental issue in providing support from orbit is the

communication, especially for what concerns communications from Mars because of long delay of the signal. Communication capabilities from space assets in Mars orbits should be considered in order to strengthen the communication strategy.

Functional Requirements can be derived from the functions in the same ways as it was done in paragraph 3.2.1, i.e. converting the functions in "shall" statements.

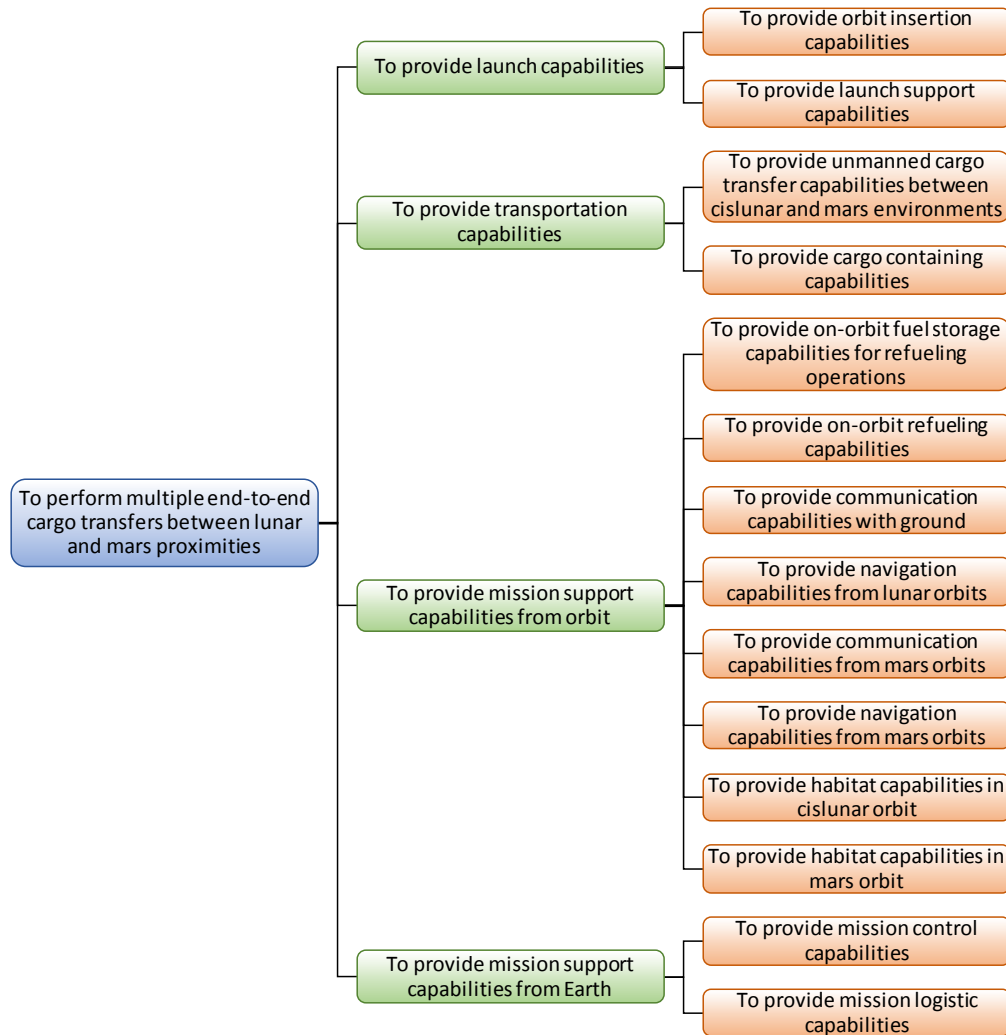


Figure 3.4: Functional Tree - System of Systems Level

Again, we have to allocate these functions to the elements able to perform them, which in this case are the Systems of the System of Systems architecture. The Functions/Products Matrix in Figure 3.5 highlights the matches between the function and the Systems. Systems identified constitute the Building Blocks of the

functional architecture at System of Systems level, the main elements involved in the mission. They are described in Table 3.1.

Building Block	Description
<i>Launch Vehicle</i>	The system in charge of inserting the ICV into the desired LEO orbit.
<i>Launch Control Station</i>	The facility necessary to handle and control launch operations from ground.
<i>ICV</i>	The Interplanetary Cargo Vehicle which has to transfer the payload and provide it with power generation, environmental protection and communications.
<i>Cargo Module</i>	The element containing the payload that has to be transferred from LOP-G to MOS.
<i>LOP-G</i>	The Lunar Orbital Platform-Gateway, a multi-modular habitable infrastructure operating in cislunar space where the ICV docks to be loaded up with cargo and where it is refueled.
<i>MOS</i>	The Mars Orbital Station, the Mars-orbiting habitable outpost needed to be provided with cargo to support its development and its operations.
<i>ORS</i>	The Orbital Refueling System, the dedicated refueling depot envisaged to enable on-orbit refueling of the ICV.
<i>Lunar Navigation Satellites</i>	Satellites system that provides ICV with guidance and navigation service in cislunar environment.
<i>Mars Communication Satellites</i>	Orbital assets in Mars proximity that provide communications services to the ICV and back to Ground Segment.
<i>Mars Navigation Satellites</i>	Satellites system providing ICV with guidance and navigation service in mars proximities.
<i>Mission Control Center</i>	Ground facility providing systems control and monitoring mission execution.
<i>Mission Logistic Center</i>	Ground facility providing logistic services and information throughout the mission.

Table 3.1: Building Blocks description

		Systems											
		LS		SS								GS	
		Launch Vehicle	Launch Control Station	ICV	Cargo Module	LOP-G	MOS	Orbital Refueling System	Lunar Navigation Satellites	Mars Communication Satellites	Mars Navigation Satellites	Mission Control Center	Mission Logistic Center
Functions	To provide orbit insertion capabilities	X											
	To provide launch support capabilities		X										
	To provide unmanned cargo transfer capabilities between cislunar and mars environments			X									
	To provide cargo containing capabilities				X								
	To provide on-orbit fuel storage capabilities for refueling operations						X						
	To provide on-orbit refueling capabilities			X									
	To provide communication capabilities with ground			X									
	To provide navigation capabilities from lunar orbits							X					
	To provide communication capabilities from mars orbits								X				
	To provide navigation capabilities from mars orbits									X			
	To provide habitat capabilities in cislunar orbit					X							
	To provide habitat capabilities in mars orbit						X						
	To provide mission control capabilities											X	
To provide mission logistic capabilities												X	

Figure 3.5: Functions/Products Matrix - System of Systems Level

Through the Functions/Products Matrix *Functional Requirements* can be refined: each previous "shall" statement now has to specify the element performing the task. Thus, for instance, *Orbit insertion capabilities shall be provided* becomes *Launch Vehicle shall provide orbit insertion capabilities*.

Through the matches highlighted in the Functions/Products Matrix in Figure

3.5 we lead the mission design to a specific direction, since we are forced to make choices between alternatives. Especially for what concerns the system associated with the function *To provide on-orbit fuel storage capabilities for refueling operations* two main viable options are possible. The task could be performed by a dedicated refueling system, i.e. a space system that is specifically introduced to enable ICV's refueling operations, or by the LOP-G, a system already foreseen in the functional architecture, since it provides habitat capabilities in cislunar orbit. However, the alternative that has been considered for this study is the former one.

3.2.3 Functional Architecture at System of Systems Level

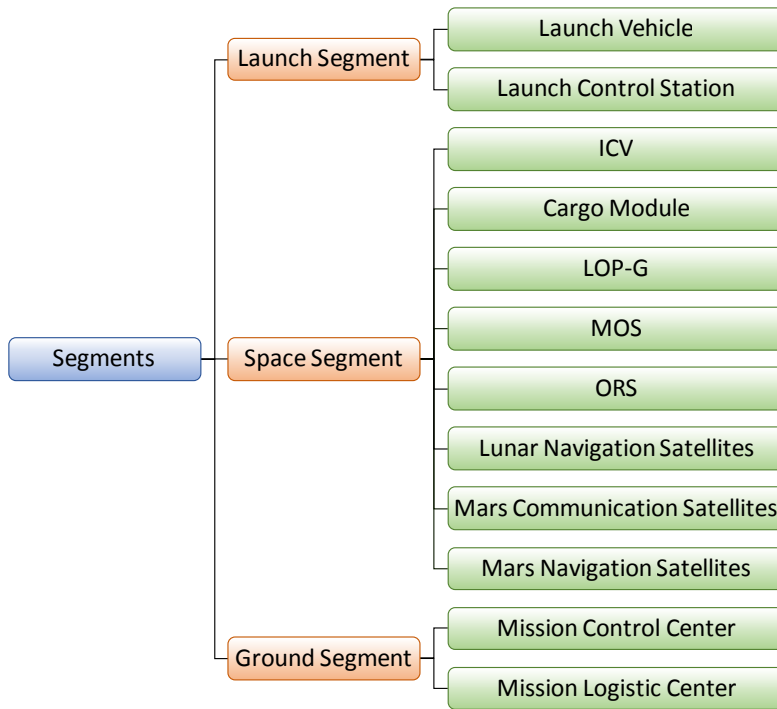


Figure 3.6: Product Tree - System of Systems Level

By simply grouping together the Building Blocks the Product Tree of the System of Systems Level in Figure 3.6 can be generated. Launch Vehicle and Launch Control Station are part of the Launch Segment, while ICV, Cargo Module, LOP-G, MOS, ORS, Lunar Navigation Satellites, Mars Communication and Mars Navigation Satellites constitute the Space Segment. Eventually, Mission Control Center and Mission Logistic Center are the facilities belonging to the Ground Segment.

From the Product Tree *Configuration Requirements* can be derived. They provide indications about the architecture composition and internal organization.

For instance, *The Ground Segment shall consist of the Mission Control Center and the Mission Logistic Center* is a configuration requirement.

Completing the functional architecture at System of Systems Level requires the determination of the connections between all the Building Block. The Connection Matrix in Figure 3.7 highlights which elements are interconnected while the Functional Block Diagram in Figure 3.8 provides additional information about the type of connections and their directionalities, especially from the ICV standpoint, which is the core system of the mission.

	Launch Vehicle	Launch Control Station	ICV	Cargo Module	LOP-G	MOS	ORS	Lunar Navigation Satellites	Mars Communication Satellites	Mars Navigation Satellites	Mission Control Center	Mission Logistic Center
Launch Vehicle												
Launch Control Station	X											
Interplanetary Cargo Vehicle	X											
Cargo Module			X									
LOP-G			X	X								
MOS			X	X								
ORS			X									
Lunar Navigation Satellites			X									
Mars Communication Satellites			X			X						
Mars Navigation Satellites			X									
Mission Control Center			X						X			
Mission Logistic Center			X								X	

Figure 3.7: Connection Matrix - System of Systems Level

During the launch, the ICV is mechanically connected with the Launch Vehicle and sends its telemetry data to it, in order to be monitored by the Launch Control Station, which communicates with the Launch Vehicle. In orbit, the ICV receives data from Lunar Navigation Satellites and Mars Navigation Satellites to elaborate its position in both cislunar and Mars proximities. In Mars vicinity communication with the Mission Control Center occurs through the Mars Communication Satellites, which release the ICV from the high power required to detect and transmit signals back to Earth. The same is true for the MOS. The ICV also exchanges data with the MOS, the LOP-G and the ORS to support rendezvous and mating

operations with these systems. Initially, the mechanical link of the ICV with both LOP-G and MOS was considered, but, after developing the Concept of Operations analysis, the one with the MOS was removed, since the ICV is always attached to the Cargo Module when it is at the MOS and the mating interface is only between the Cargo Module and the MOS. At the LOP-G, instead, the mechanical link can be present or not, depending on the scenario considered among those developed in Chapter 5. A fluidic and a mechanical link exists between the ICV and the ORS, since the ICV is refueled at the dedicated refueling system. When transferring the Cargo Module, the ICV is not only mechanically attached to it but also provides it with power and receives from it telemetries to monitor its state of health.

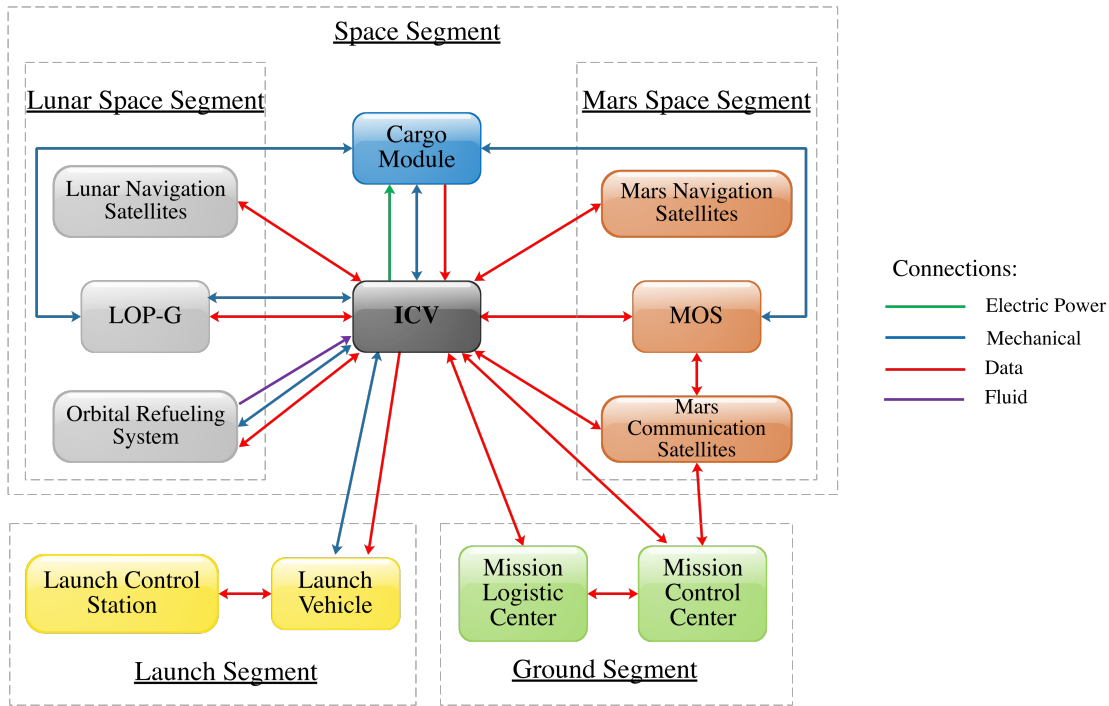


Figure 3.8: Functional Block Diagram - System of Systems Level

From the Connection Matrix *Interface Requirements* can be set down. They verbalize for each Building Block with which other elements shall it interface. For instance, *ICV shall interface with ORS* is an interface requirement deriving from the Connection Matrix. Interface Requirements are then refined after developing the Functional Block Diagram, i.e. new requirements are generated specifying types and directions of connections. Considering the previous example, the requirement is detailed in four new requirements:

1. *ICV shall mechanically interface with ORS*

2. *ICV shall transmit data to ORS*
3. *ICV shall receive data from ORS*
4. *ICV shall be supplied with fuel by ORS*

Now that all Systems constituting the groundwork of the mission architecture have been identified and their main relations determined, we will focus in the following chapter on the ICV system to provide its own functional characterization and determine how it should be internally arranged.

Chapter 4

Functional Analyses at System and Subsystem Levels

4.1 Functional Analysis at System Level

4.1.1 Subsystems Identification

To identify the elements which are part of the functional architecture at System Level, we first extent the Functional Tree of the previous level exclusively for what concerns the function assigned to the ICV, that were:

1. To provide unmanned cargo transfer capabilities between cislunar and Mars environments;
2. To provide communication capabilities with ground;
3. To provide on-orbit refueling capabilities.

These functions are the starting point for the definition of the Functional Tree at System Level and must be decomposed to obtain functions related to subsystems tasks. By asking how the ICV functions can be performed, we can simplify them obtaining the Functional Tree shown in Figure 4.1.

Several capabilities are required to perform the first function: propulsion, propellant management and power management are necessary to thrust the vehicle. Power management capabilities allow also providing electric power to the equipment on board the spacecraft. Guidance capabilities determine the desired path of travel and how to reach it. Navigation and control, respectively, resolve current state vector and determine the necessary thrust to get the spacecraft where

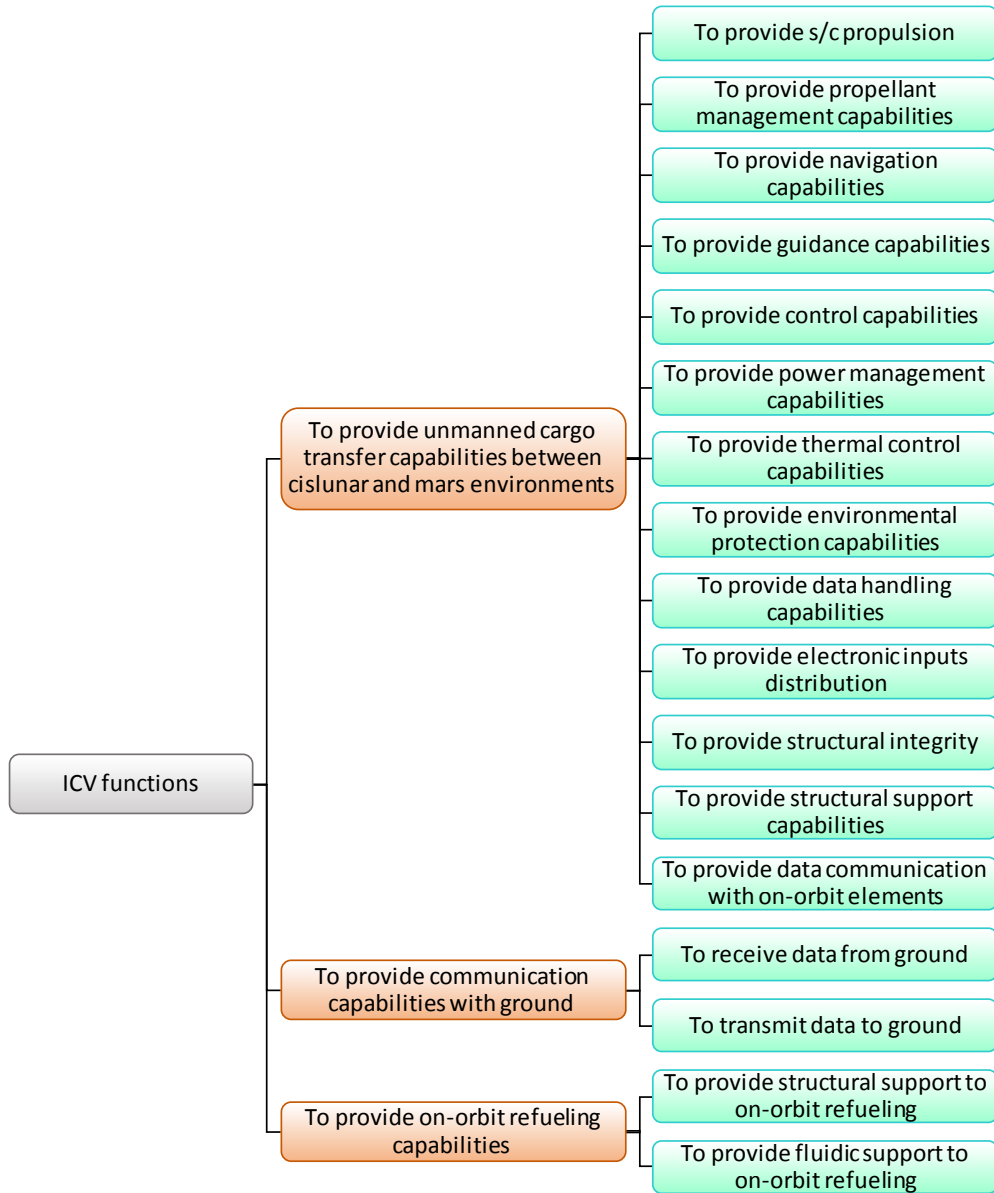


Figure 4.1: Functional Tree - Systems Level

it needs to go. Data handling capabilities deal with data collecting and distribution throughout the vehicle. Furthermore, transferring both power and data on the spacecraft requires electronic inputs distribution. To safely move in space the ICV also needs environmental protection and thermal control capabilities, as well as structural integrity capabilities to preserve internal volumes distribution and structural support capabilities to sustain spacecraft equipment in various mission phases. Data communication with on-orbit elements is necessary to interact with

		Subsystems								
		PROP	AOCS	EPS	DMS	TT&C	TCS	S&M	REF	HARN
Functions	To provide s/c propulsion	X								
	To provide propellant management capabilities	X								
	To provide navigation capabilities		X							
	To provide guidance capabilities		X							
	To provide control capabilities		X							
	To provide power management capabilities			X						
	To provide thermal control capabilities						X			
	To provide environmental protection capabilities							X		
	To provide data handling capabilities				X					
	To provide electronic inputs distribution									X
	To provide structural integrity							X		
	To provide structural support capabilities							X		
	To provide data communication with on-orbit elements					X				
	To receive data from ground					X				
	To transmit data to ground					X				
To provide structural support to on-orbit refueling								X		
To provide fluidic support to on-orbit refueling								X		

Figure 4.2: Functions/Products Matrix - System Level

the other space systems constituting the mission architecture and identified in Chapter 3.

For the second function both reception from ground and transmission to ground shall be ensured. To perform the third function it should be considered that a mechanical interface providing both fluidic and structural support is required to carry out refueling operations.

The Functions/Products Matrix shown in Figure 4.2 allows the identification of the following subsystems:

Subsystem	Description
<i>PROP</i>	The <i>Propulsion Subsystem</i> provides thrust to adjust orbit and attitude and to manage angular momentum.
<i>AOCS</i>	The <i>Attitude and Orbit Control Subsystem</i> provides determination and control of attitude and orbital position. It stabilizes and orients the vehicle, providing pointing of the spacecraft and its appendages, such as antennas and solar arrays.
<i>EPS</i>	The <i>Electrical Power Subsystem</i> supplies spacecraft equipment with electric power. It generates and stores electric power, regulates and distributes it throughout the spacecraft.
<i>DMS</i>	The <i>Data Management Subsystem</i> validates and distributes command data and collects and formats telemetry data for the downlink. It also provides data storage.
<i>TT&C</i>	The <i>Tracking Telemetry and Command Subsystem</i> provides communication with ground facilities and other spacecrafts. It allows performing spacecraft tracking by retransmitting received range tones or by providing coherence between received and transmitted signals.
<i>TCS</i>	The <i>Thermal Control Subsystem</i> maintains equipment within allowable temperature limits for each mission phase.
<i>S&M</i>	The <i>Structures and Mechanisms Subsystem</i> provides the support structure to carry and protect spacecraft equipment. It includes mechanical interfaces with on-orbit systems.
<i>REF</i>	The <i>Refueling Subsystem</i> provides mechanical and fluidic couplings necessary to carry out refueling operations at the ORS.
<i>HARN</i>	The <i>Harness Subsystem</i> consists of all wiring, electronics backplane and electric interface boards to distribute data and provide electric power distribution.

Table 4.1: Subsystems description

Functional Requirements can be derived from the Functional Tree and refined through the Functions/Products Matrix as indicated in Paragraph 3.2.2 for the System of Systems Level. Since more details are available with every level of the Functional Analysis, more specific functions are now expressed in the Functional Requirements. Therefore, Performance Requirements can be introduced to describe quantitatively how well those functions must be performed. Table 4.2 provides examples of Performance Requirements deriving from Functional Requirements. Numerical values are indicated with "TBD", meaning that they're yet to be defined in subsequent in-depth system sizing.

<i>Functional Requirements</i>	<i>Performance Requirements</i>
<i>PROP shall provide spacecraft propulsion</i>	<i>PROP shall provide TBD Ns of total impulse; PROP shall provide TBD N of thrust level</i>
<i>PROP shall provide propellant management capabilities</i>	<i>PROP shall manage TBD kg of propellants</i>
<i>AOCS shall provide control capabilities</i>	<i>AOCS shall provide TBD° of control accuracy; AOCS shall provide TBD rad/s of speed of response; AOCS shall provide TBD Nm of torque capability</i>
<i>EPS shall provide power management capabilities</i>	<i>EPS shall provide power to operate the equipment in compliance with power requirements for every mission phase</i>
<i>TCS shall provide thermal control capabilities</i>	<i>TCS shall maintain equipment within operative temperatures</i>
<i>TT&C shall provide data communications with on-orbit elements</i>	<i>TT&C shall receive data at a rate of TBD bit/s from on-orbit elements; TT&C shall transmit data at a rate of TBD bit/s to on-orbit elements; TT&C shall detect signal from on-orbit elements within TBD allowable error rate</i>
<i>DMS shall provide data handling capabilities</i>	<i>DMS shall transmit data at rates that supports command and telemetry requirements at any mission phase</i>
<i>HARN shall provide electronic inputs distribution</i>	<i>HARN shall dissipate power not exceeding TBD % of operating power</i>

Continued on next page

<i>Functional Requirements</i>	<i>Performance Requirements</i>
<i>S&M shall provide structural integrity</i>	<i>S&M shall guarantee fundamental frequencies of the S/C within the requirements of the Launch Vehicle to avoid dynamic coupling; S&M shall support the mechanical static and dynamic loads encountered during ICV entire lifetime, including: ground operations, launch, deployment and on-orbit operations</i>
<i>REF shall provide fluidic support to on-orbit refueling</i>	<i>REF shall ensure correct couplings between the ICV and the ORS</i>

Table 4.2: Examples of Performance Requirements deriving from Functional Requirements

4.1.2 Functional Architecture at System Level

Since the ICV is constituted by all the subsystems identified, its Product Tree easily results as represented in Figure 4.3.

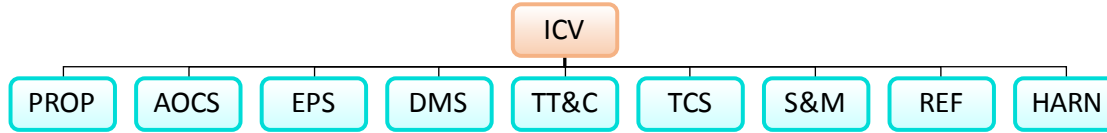


Figure 4.3: Product Tree - System Level

To properly interconnect all the subsystems determined, it is necessary to understand the essential needs that should be satisfied to make them work.

The PROP, AOCS, TCS, REF, TT&C and DMS subsystems all need to be supplied with electric power by the EPS. The PROP subsystem exploits electric power to generate thrust. The AOCS needs electric power for controllers, in charge of processing the ICV's attitude and orbit position, and for actuators, which are asked to change attitude and orbital position. The TCS subsystem also includes controllers to monitor equipment temperatures and electrical devices to control them. The REF subsystem requires electric power to handle couplings and valves between the ICV and the ORS for refueling operations. The TT&C needs electric power for transmitting and receiving devices, whereas the DMS for the central processor and data handling equipment.

The DMS gathers telemetries from the other subsystems and it formats them for the downlink. It needs to interface with the TT&C, to which it delivers the telemetry data and from which it receives commands. DMS then distribute commands to other subsystems. TT&C is in charge of transmitting telemetries received from the DMS to ground. Furthermore, it also has to receive and validate command data flowing from ground and from various on-orbit systems to the ICV.

The HARN includes all wirings allowing both data and power distributions while the S&M provides structural support and sustainment to all other subsystems. Eventually, one last connection can be identified at this level: it is the fuel flowing from the REF to the PROP during refueling operations.

In view of these considerations, the Connection Matrix and the Functional Block Diagram are those of Figures 4.4 and 4.5.

	PROP	AOCS	EPS	DMS	TT&C	TCS	S&M	REF	HARN
PROP									
AOCS									
EPS	X	X							
DMS	X	X	X						
TT&C			X	X					
TCS			X	X					
S&M	X	X	X	X	X	X			
REF	X		X	X					
HARN	X	X	X	X	X	X	X	X	

Figure 4.4: Connection Matrix - System Level

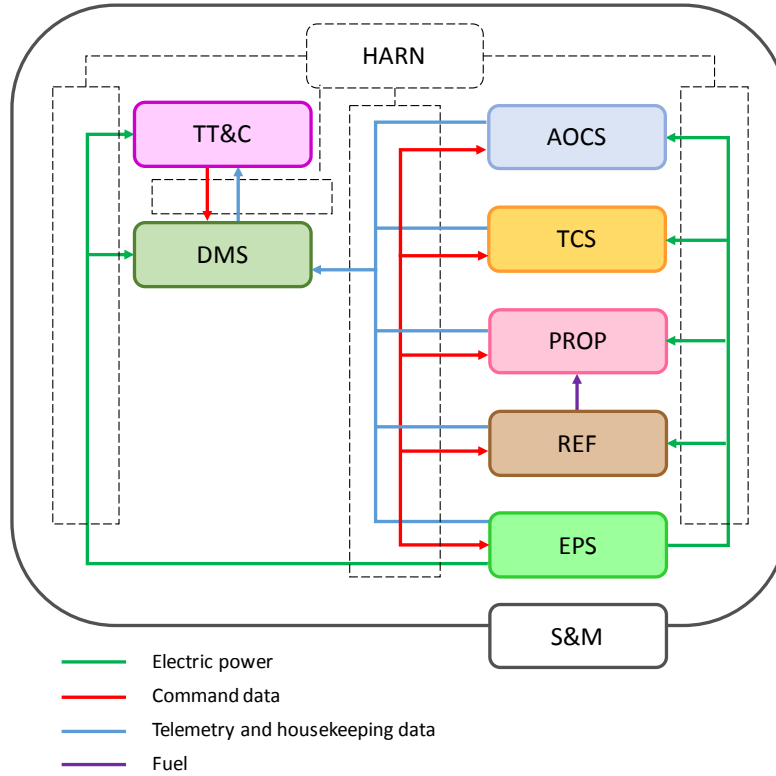


Figure 4.5: Functional Block Diagram - System Level

4.2 Functional Analysis at Subsystem Level

The definition of the next lower layer of the ICV architecture requires going further in the decomposition of the basic functions determined in the previous level. For each subsystem, the analysis leads to identify the main equipment, i.e. the fundamental elements which are necessary to perform the subsystem top-level function. In the following paragraphs, the components identification is given for each subsystem. After identifying all components of all subsystems, the functional architecture for the Subsystem Level as a whole is presented at the end of this section.

4.2.1 Propulsion Subsystem

The PROP subsystem is responsible for providing spacecraft propulsion and propellant management capabilities. To fulfill these tasks, the basic functions that

shall be ensured are indicated in the Functional Tree in Figure 4.6. Elements able to perform them are shown in the Functions/Product Matrix on the right side of the figure. They include:

- Power Processing Unit (PPU)
- Thruster Units
- Fuel Tanks
- Feeding System

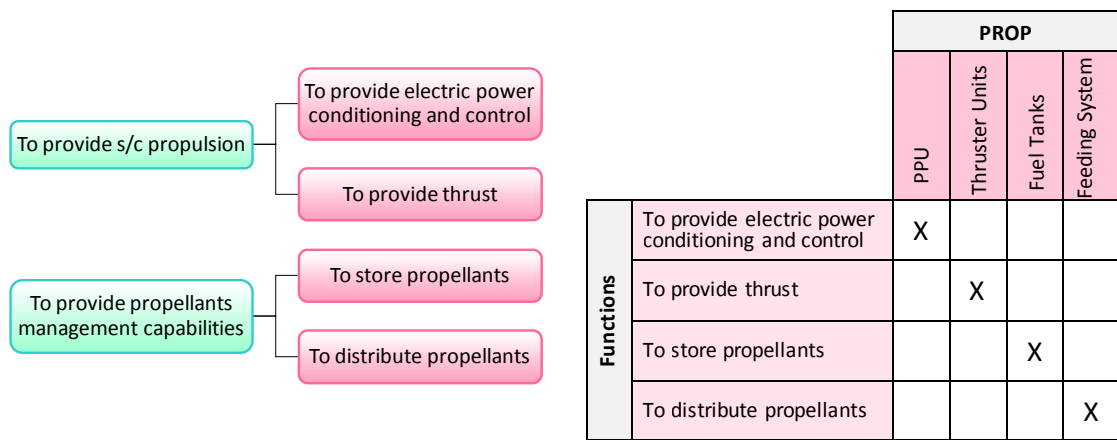


Figure 4.6: Functional Tree (left) and Functions/Products Matrix (right) - PROP

Thruster Units are in charge of providing thrust, each of them consists of a high-power Hall Effect Thruster (HET) and at least one high-current hollow cathode. In the Electric Propulsion, Hall Effect Thrusters have the advantage of operating with a high value of thrust to power ratio compared to the Gridded Ion Engines (GIEs). They use crossed electric and magnetic fields to generate and accelerate ions. The magnetic field traps electrons emitted by the hollow cathode, retarding their flow to the anode, so that they can collide with the neutral propellant ionizing it. The generated ions are then accelerated by the electric field. Considering the latest technological achievements, we can assume for a single thruster a thrust of $1000mN$ and a Specific Impulse of $2500s$.

The PPU is used to generate the electrical discharge between the cathode and the annular anode through which the propellant, usually Xenon, is injected. It also supplies power to coils to obtain the magnetic field. The PPU provides electric power conditioning and control in response to the thruster performances. It is supplied by the spacecraft's Power Conditioning and Distribution Unit (PCDU), part

of the Electrical Power Subsystem. The On-Board Computer (OBC) is responsible for PPU control: it receives housekeeping data from the PPU and transmits commands to it.

High-pressure Xenon is stored in Fuel Tanks and it is supplied via the Feeding System to the Thruster Units. The standard Feeding System for Electric Propulsion applications employs a pressure regulator to manage the propellant pressure to a constant pressure over mission life. After the regulation of the pressure, the propellant is fed to the thrusters and controlled by the PPU. The PPU adjusts the anode voltage according to the thrust required by the OBC. As the PPU, also the Feeding System exchanges telemetries and command data with the OBC through Remote Interface Units (RIUs). OBC and RIUs are part of the Data Management Subsystem.

The Functional Block Diagram in Figure 4.7 illustrates PROP components interconnections and links with components from other subsystems.

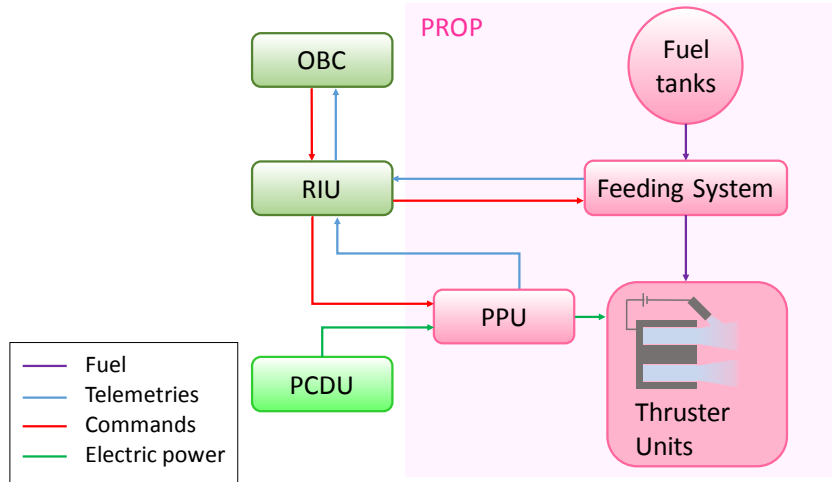


Figure 4.7: Functional Block Diagram - PROP

4.2.2 Attitude and Orbit Control Subsystem

The AOCS subsystem shall ensure navigation, guidance and control capabilities. To perform these tasks, the basic functions that shall be provided are indicated in the Functional Tree in Figure 4.9. Components able to perform the AOCS basic functions are identified through the Functions/Products Matrix illustrated in Figure 4.9 on the right side. They are:

- Orbit Sensors

- Attitude Sensors
- AOCS On-Board Computer (AOCS OBC)
- AOCS Actuators

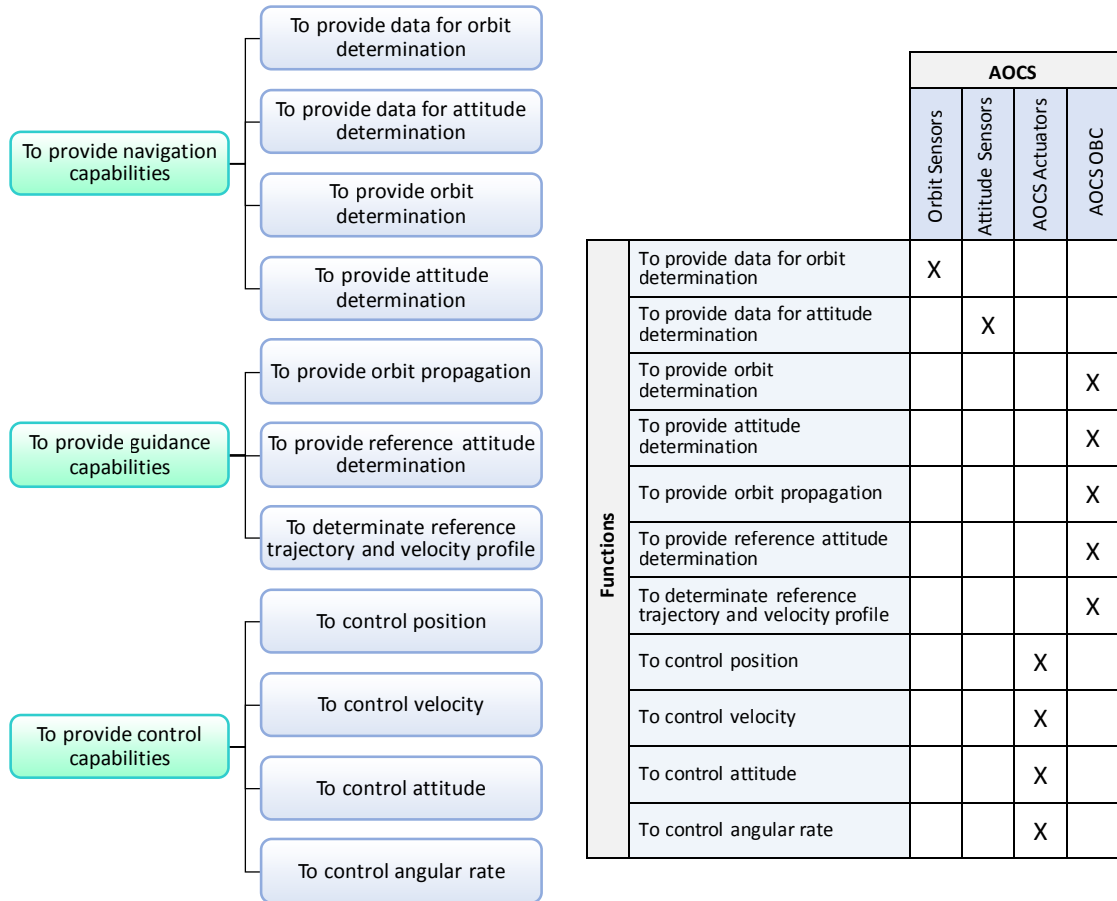


Figure 4.8: Functional Tree (left) and Functions/Products Matrix (right) - AOCS

Orbit Sensors and Attitude Sensors provide measurements for navigation. Navigation deals with the determination, at a given time, of the spacecraft's attitude and orbit position. The AOCS OBC processes measurements from sensors to reconstruct both orbit and orientation of the ICV.

The AOCS OBC uses algorithms to propagate orbits and generates and tracks relative guidance trajectory. Besides determining the desired trajectory from the ICV's current location to a designated target, it also define changes in velocity for following that path. Furthermore, it determine the reference attitude that the ICV

has to follow to satisfy pointing requirements, such as those for communications antennas and solar arrays.

The AOCS Actuators allow forces manipulation in order to follow both the desired trajectory and reference attitude. AOCS Actuators are consequently in charge of control both position and velocity as well as attitude and angular rate. As shown in Figure 4.9 they receive commands from the AOCS OBC, via a RIU, after the sensor telemetries elaboration.

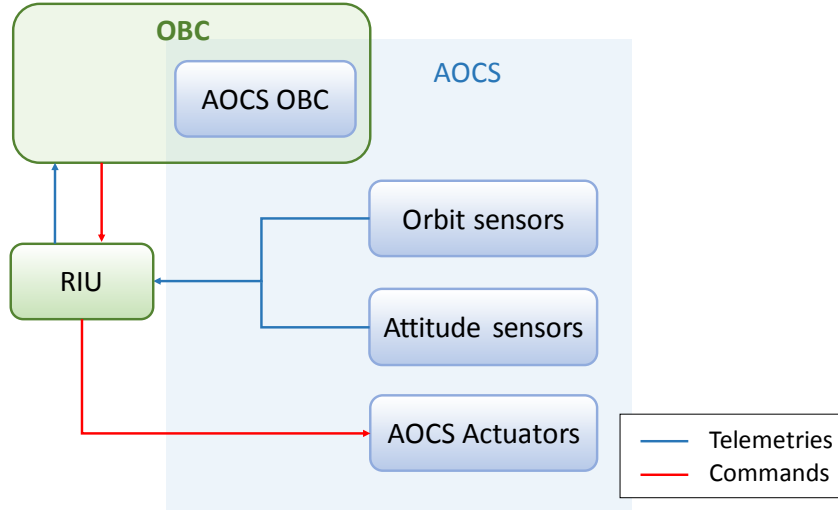


Figure 4.9: Functional Block Diagram - AOCS

4.2.3 Electrical Power Subsystem

The EPS is in charge of providing power management capabilities. This means it has to generate power, to store energy and to provide power regulation and distribution, as indicated in the Functional Tree in Figure 4.10. Allocating these functions to components produce the Functions/Products Matrix on the right side of the figure. A basic architecture for the EPS consists of:

- Solar Arrays
- Batteries
- Power Conditioning and Distribution Unit (PCDU)

Solar Arrays provides conversion of Sun energy into usable electrical power for the entire spacecraft. Once electrical energy is obtained, it has to be stored

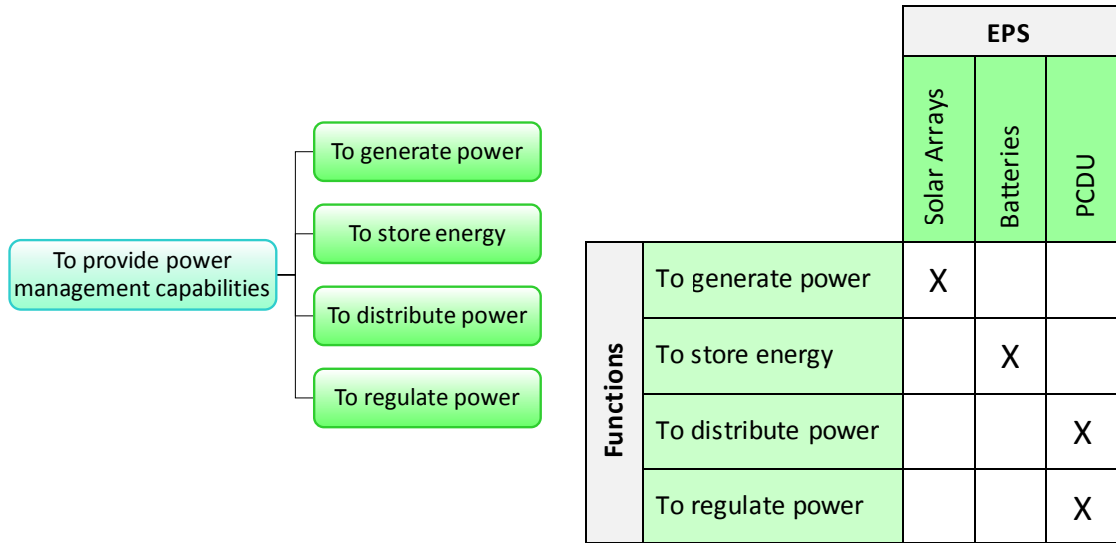


Figure 4.10: Functional Tree (left) and Functions/Products Matrix (right) - EPS

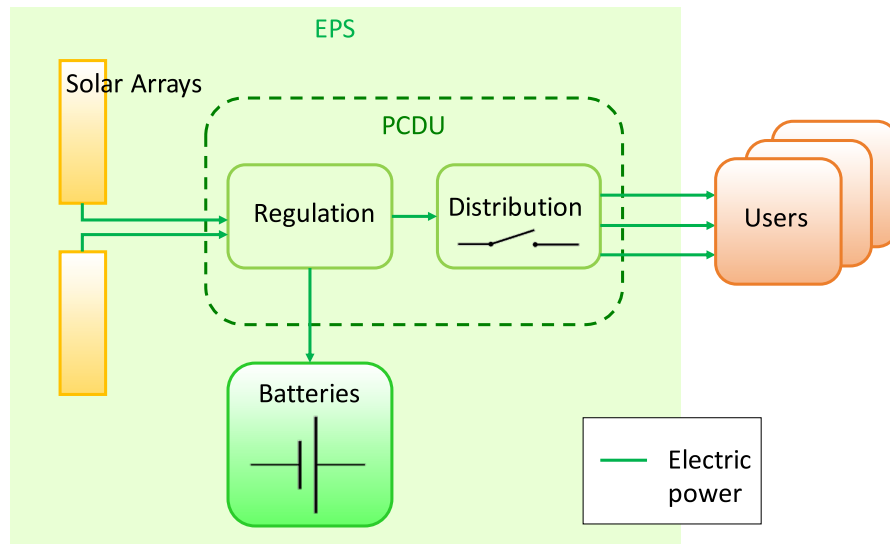


Figure 4.11: Functional Block Diagram - EPS

in batteries, to be used when the ICV is in shadow. Electric power has to be distributed to the various subsystems with a defined regulation. This last task is performed by the Power Conditioning and Distribution Unit (PCDU).

In fact, the PCDU shall condition, control, and distribute electrical energy during each ICV mission phases in according with the requirements of the various primary power users of the spacecraft. Furthermore, it shall regulate power from Solar Arrays for battery charging and shall provide switching that allows the

batteries to supply power when needed. It is also expected to provide protection against short circuits and to isolate faults.

Functional Block Diagram in Figure 4.11 shows how EPS components can be arranged.

4.2.4 Data Management Subsystem

The DMS is responsible for data management. To simplify this task, decomposition of the DMS top function is provided in the Functional Tree in Figure 4.12.

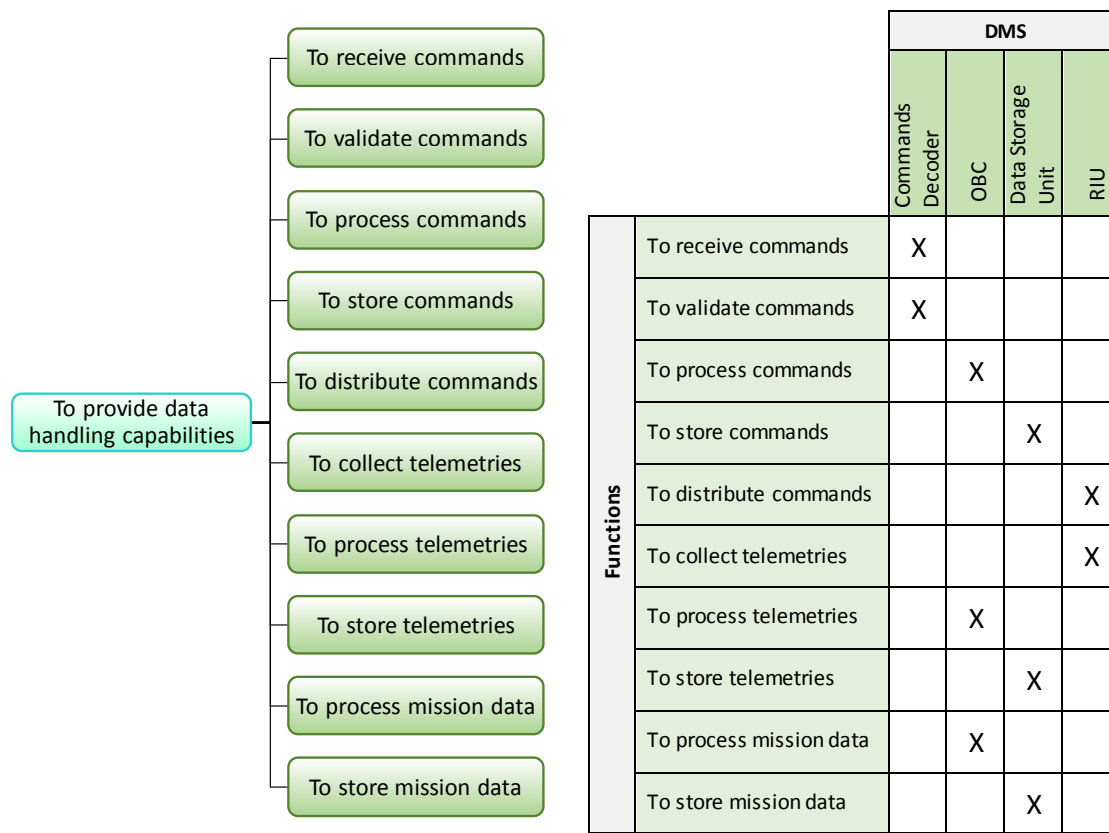


Figure 4.12: Functional Tree (left) and Functions/Products Matrix (right) - DMS

Through the Functions/Products Matrix in Figure 4.12 the DMS basic functions are matched with the following components:

- Commands Decoder
- On-Board Computer (OBC)

- Data Storage Unit
- Remote Interface Unit (RIU)

The Commands Decoder acts as a filter rejecting messages that do not pass validation criteria. validated commands are processed in the OBC and can either be stored in the Data Storage Unit to be executed later, in this case they are associated to timer-execute commands, or they can be delivered directly to the users, through RIUs, as indicated in the Functional Block Diagram in Figure 4.13.

A RIU (also called RTU: Remote Terminal Unit) is a unit usually present on medium-large size spacecraft and represents an example of distributed control system implementation. It offloads the OBC from analogue and digital data acquisition and from actuators control tasks. Through RIUs telemetries from various users are gathered to be elaborated and formatted in the OBC with other mission data.

The DMS interfaces with the TT&C subsystem from which it receives commands and to which it sends the formatted telemetry stream.

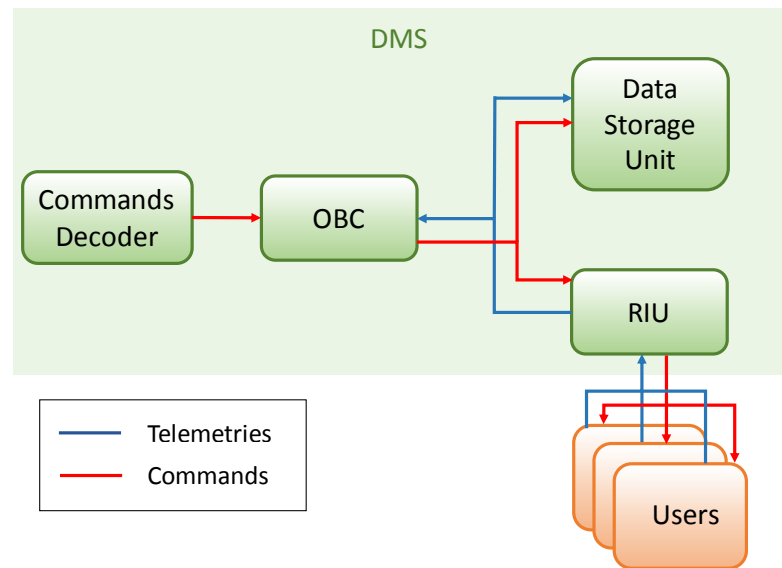


Figure 4.13: Functional Block Diagram - DMS

4.2.5 Tracking, Telemetry and Command Subsystem

The TT&C subsystem has to provide communication with on-orbit elements and with ground. These tasks have been simplified through the decomposition

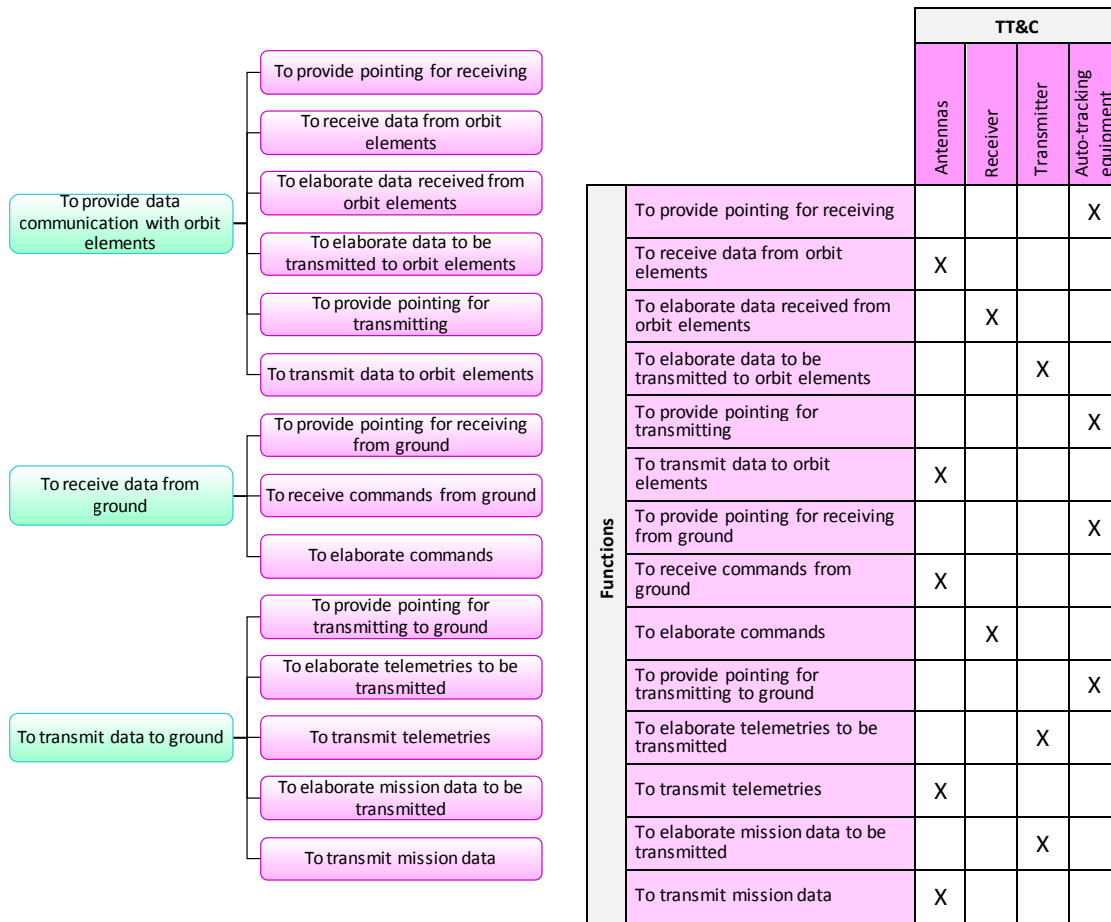


Figure 4.14: Functional Tree (left) and Functions/Products Matrix (right) - TT&C

of TT&C top level functions, as shown in the Functional Tree in Figure 4.14. The subsystem is responsible for receiving and demodulating signals from ground and from on-orbit systems, as well as modulating and transmitting signals to ground and on-orbit systems. The subsystem also allows to track the spacecraft by retransmitting received range tones or providing coherence between received and transmitted signals.

The basic elements of the TT&C Subsystem identified in the Functions/Products Matrix of Figure 4.14 are:

- Antennas
- Receiver
- Transmitter

- Auto-tracking equipment

The Antenna is the device that transmits and receives signals. In transmission, the antenna radiates energy from the current supplied by the Transmitter in form of electromagnetic waves. In reception, conversely, it intercepts power of electromagnetic wave in order to produce an electric current that is then transmitted to the Receiver. The ability to communicate requires clear field of view for the ICV antennas and sufficient received power to detect the signal with acceptable error rate. The antennas are expected to provide pointing for receiving and transmitting data with the various systems and facilities with which the ICV has to communicate.

Auto-tracking equipment performs closed-loop antenna pointing by generating error signal for the AOCS Subsystem, so it can point the antenna, as indicated in Figure 4.15.

The Transmitter provides modulation and amplification of the signal to be transmitted. The modulation is the process of varying a carrier signal properties with a baseband signal that contains information to be transmitted. The signal so obtained is the "modulated signal" and has to be amplified prior transmission.

The Receiver deals with the amplification of the received signal and its demodulation, i.e. the extraction of the original information-bearing signal from the carrier wave.

Functional Block Diagram in Figure shows TT&C components and their connections.

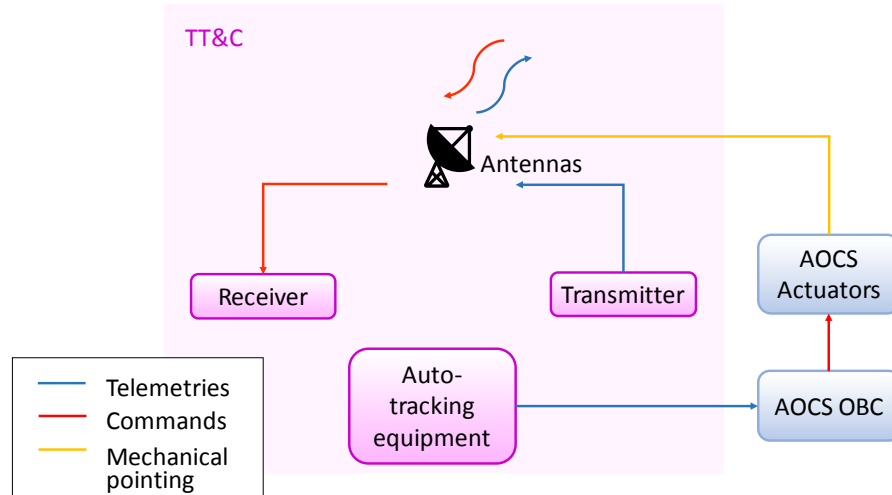


Figure 4.15: Functional Block Diagram - TT&C

4.2.6 Thermal Control Subsystem

The TCS top function has been extended in the Functional Tree in Figure 4.16. The subsystem is in charge of maintaining all ICV components and subsystem within their required temperature limits during the whole mission. It has also to ensure that temperature gradient requirements are met to minimize thermal distortion. The thermal control techniques must cope with the external environment, which can vary in a wide range, as the spacecraft is exposed to deep space, or to solar or planetary flux. Furthermore, it has to reject the internal heat generated by the operation of the spacecraft itself. Thermal control techniques are used to protect the equipment from overheating and from too cold temperature and can be either passive or active. Passive techniques requires no input power for thermal regulation, they make use of materials, surface finishes and coatings to strike a balance between the heat absorbed and the heat radiated to space. Active thermal control is necessary for components that have stringent temperature requirements or which dissipate large amount of electrical power. It maintains the temperatures by means of electrical devices such as electrical heaters or thermo-electric coolers.

Components identified through the Functions/Products Matrix in Figure 4.16 are:

- Heat Pipes
- Multilayer Insulation Blankets (MLI Blankets)
- Radiators
- Electrical Heaters
- TCS On-Board Computer (TCS OBC)
- Temperature Sensors

Heat pipes are used to collect heat from localized sources and transport it to radiators where it is rejected. If heat pipes are used, it is therefore not necessary to mount all components to be cooled directly on radiator panels. A heat pipe is a passive thermal control technique that uses a closed two-phase fluid-flow cycle to transport large quantities of heat without the use of electrical power.

MLI blankets are other common passive technique for thermal insulation. Most spacecraft are covered with them except on radiator that, instead, have to reject internally generated heat. MLI blankets are composed of multiple layers of low-emittance film with low conductivity between the layers. They are typically used to protect internal propellant tanks and propellant lines.

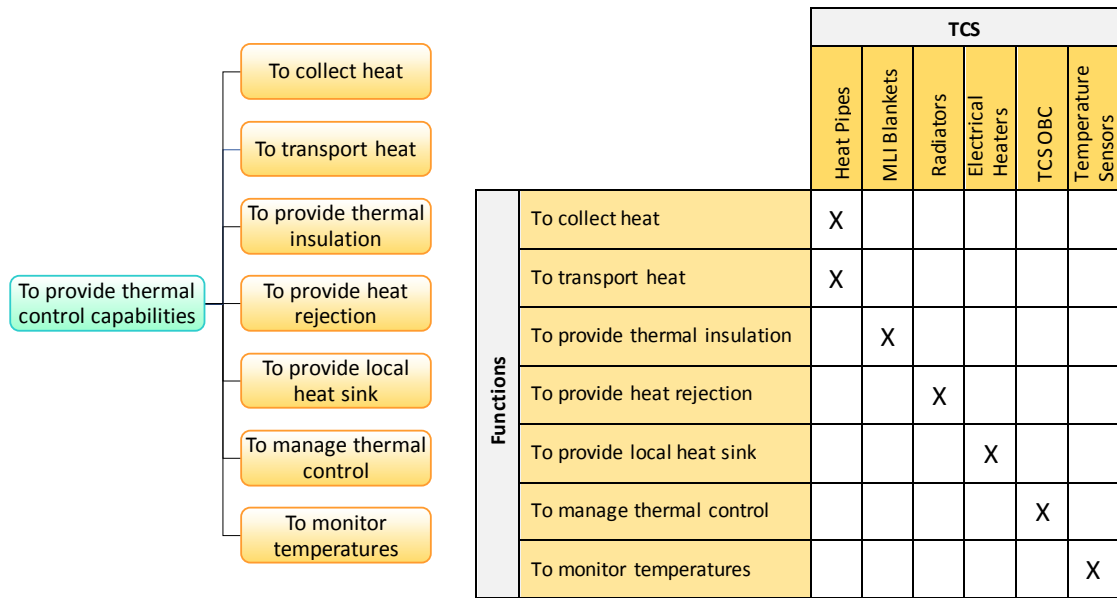


Figure 4.16: Functional Tree (left) and Functions/Products Matrix (right) - TCS

Radiators are panels that provide spacecraft's waste heat rejection by infrared (IR) radiation from their surfaces. Sources of heat for the ICV include solar radiation, planetary reflection and IR radiation, electrical energy dissipated in electrical components, impingement of plume from thrusters on the external surfaces of the spacecraft.

Electrical heaters are used either to protect components from getting too cold or to make up for heat that is not dissipated in a electric component after it is turned off. They commonly consist of an electrical resistance element arranged between two sheets of electrically insulating material. They are coupled with sensors and controllers to provide very precise temperature control.

The TCS OBC is the processing unit in charge of control electrical heaters: it reads temperature from telemetry sensors and sends signals to turn heaters on and off through a RIU.

Temperature sensors provide the TCS OBC with temperature measurements. They are in the form of integrated circuits and exploit the temperature-sensitive voltage vs. current characteristics of semiconductor diodes. By exciting the sensor via a known current, it is possible to correlate the sensor's analog voltage level into a temperature measure.

The TCS Functional Block Diagram in Figure 4.17 shows the schematic arrangement of the TCS components in relation to the equipment whose temperature has to be controlled.

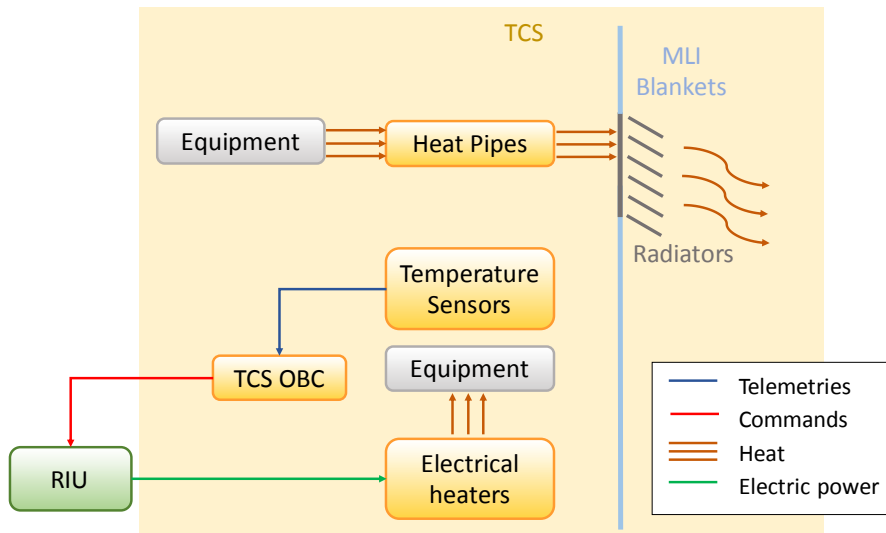


Figure 4.17: Functional Block Diagram - TCS

4.2.7 Structures and Mechanisms

The S&M subsystem provides structural support to sustain subsystems and components in each mission phase and during different mission operations. It preserve the structural integrity of the ICV and protect it from the external environment, with special attention to space radiation. These functions can be divided in low level function as indicated in the Functional Tree in Figure 4.18. Components performing these tasks are identified in the Functions/Products Matrix on the right side of the figure. They are:

- Radiation Shields
- Primary Structure
- Secondary Structure
- Meteoroid/Debris Protection System Panels (MDPS Panels)
- Docking Interface (Docking I/F)
- Grasping Interface (Grasping I/F)

Radiation Shields are barriers aimed to isolate electrical devices and cables from radiation damage caused by charge particles. Charged particles are present in space and carry enough energy to liberate electrons from atoms, creating electrical charges concentration and undesirable electric fields inside the semiconductor materials. Source for these particles are:

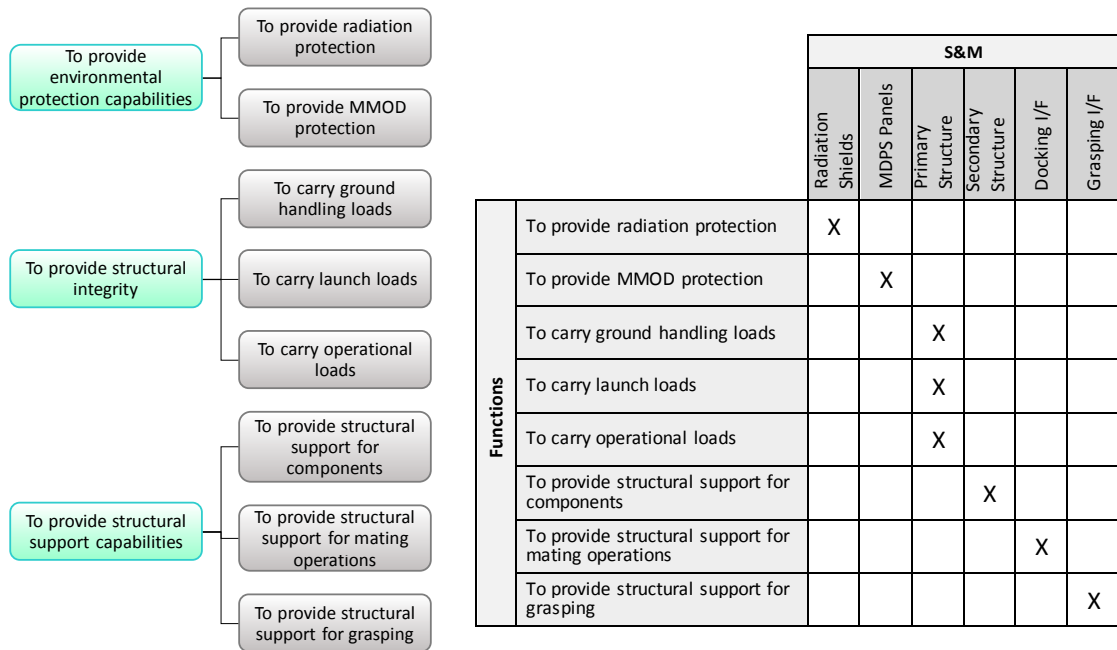


Figure 4.18: Functional Tree (left) and Functions/Products Matrix (right) - S&M

- Solar Particle Events (SPEs): energetic protons emitted during the coronal mass ejection of the Sun;
- Galactic Cosmic Rays: high-energy particles coming from outside the Solar System;
- Van Allen radiation belts: energetic particles confined around the Earth's magnetic field lines.

The Primary Structure represent the main load-carrying structure. It shall support the mechanical static and dynamic loads encountered during ICV entire lifetime, including: ground operations, launch, deployment and on-orbit operations. This structure provides the attachments with the Cargo Module and the Launch Vehicle.

The Secondary Structure consists of deployables and supports for components and is attached to the primary structure, to which it transfers loads. It provides mounting provisions for solar arrays and antennas and supports wire bundles, propellant lines, non-structural doors, and brackets for components.

The ICV will be exposed to natural meteoroids and man-made orbital debris, impacting at hypervelocity at the vehicle surface during the mission. Both can cause severe damage to the Primary Structure and subsystems. The MPDS Panels

act as bumper-panels: they decelerate the impacting particles and, depending on mass and velocity, they can fragment, melt and vaporize them. MPDS panels are made of metallic sheets and are fixed to the Primary Structure.

The Docking I/F is a mating mechanism that supports docking operations at the standardized docking ports the ICV shall interface with during the mission. The mission scenarios analysis developed in Chapter 5 brings out the need of a Docking I/F to mate with the Cargo Module and, in one of the two scenarios, also with the ORS.

The Grasping I/F is a mechanism that allow the ICV to be grabbed by a robotic arm. The need for a Grasping I/F arise in one of the two scenarios analyzed in Chapter 5.

4.2.8 Refueling Subsystem

The REF subsystem shall provide structural and fluidic support to on-orbit refueling. These functions have been decomposed in simpler functions in the Functional Tree shown in Figure 4.19. Through the Functions/Products Matrix on the right side, the following refueling provisions have been identified:

- Fluid Plane
- Fluid Couplings
- Electrical Connector
- Refueling Valves
- Refueling Tanks

The Fluid Plane is a mechanical plate intended to guide the correct alignment between the ICV and the ORS refueling interfaces. It provides the mounting structure for the Fluid Couplings and the Electrical Connector. The Fluid Couplings represent the fluid connections for propellants. Once they've been connected with the equivalent couplings on the ORS, they allow fuel transfer from the servicing system to the ICV. The Electrical Connector provides the electrical link between the ICV and the station. Electric power is used to operate the Refueling Valves, which transfer the fuel in the Refueling Tanks.

Figure 4.20 illustrates the Functional Block Diagram for the REF subsystem.

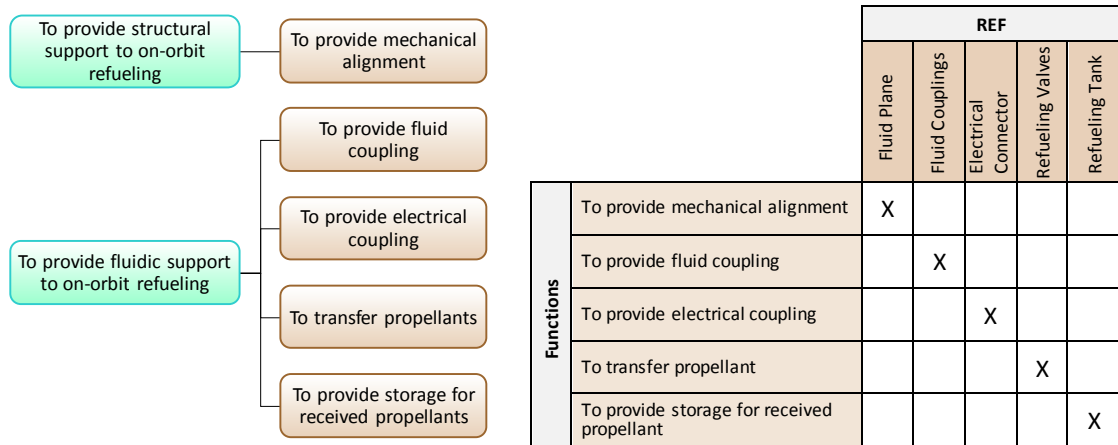


Figure 4.19: Functional Tree (left) and Functions/Products Matrix (right) - REF

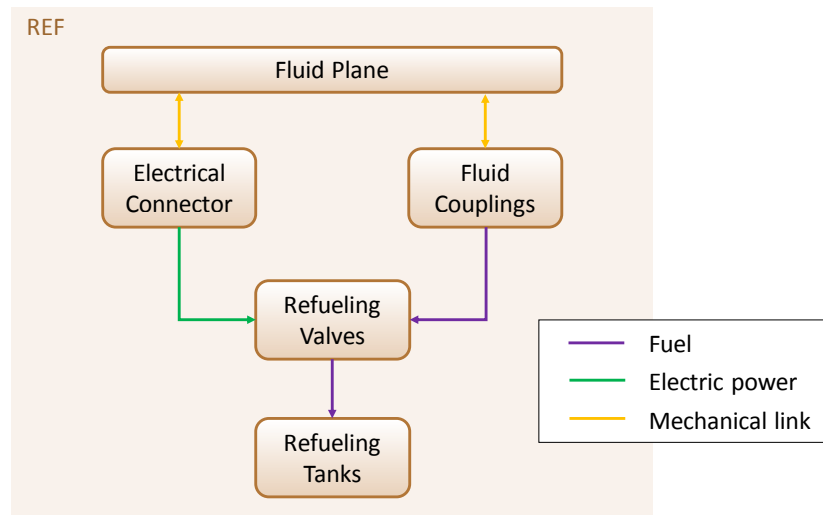


Figure 4.20: Functional Block Diagram - REF

4.2.9 Harness Subsystem

As indicated in the Functional Tree in Figure 4.21, the HARN subsystem is responsible for the distribution of telemetries and commands, as well as of electric power throughout the spacecraft. In particular, as shown in the Functions/Products Matrix of Figure 4.21, components that shall perform these tasks are:

- Data Bus: it covers all hardware components, software and communication protocols that allow data to be transferred between units;

- Electric Power Harness: it consists of the assembly of electrical cables and wires which transmit electrical power throughout the vehicle.

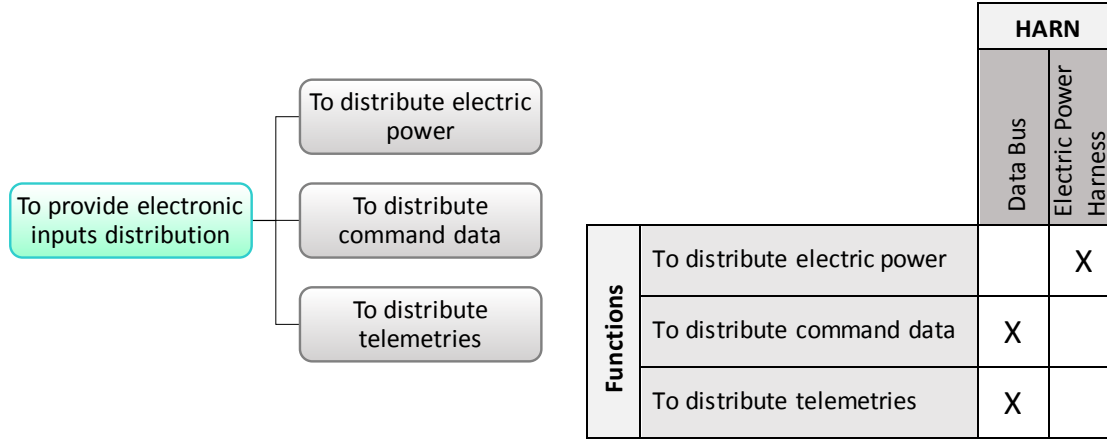


Figure 4.21: Functional Tree (left) and Functions/Products Matrix (right) - HARN

4.2.10 Functional Architecture at Subsystem Level

To complete the functional description of the ICV at Subsystem Level, we need to determine how all the components identified in previous paragraph are interrelated.

The Connection Matrix in Figure 4.22 indicates which elements are interfaced, and provides the groundwork for the development of the Functional Block Diagram in Figure 4.23.

As described in paragraph 4.2.1 the PPU interfaces with the Thruster Units, the PCDU and the RIU. It also shall have heat removed by heat pipes and shall be thermally monitored through Temperature Sensors and protected by Radiation Shields. In fact, Radiation Shields act as a barrier to protect electrical devices and cables from radiation damages. For this reason, besides shielding the PPU, they also interface with Batteries, the PCDU, the Electrical Heaters and all other electrical devices, and with the Data Bus and the Electric Power Harness.

Temperature Sensors and Electrical Heaters interfaces with all the elements that need accurate thermal monitoring and control, for example, the Fuel Tanks. In the Fuel Tanks Xenon temperature has stringent requirements that shall be satisfied. Furthermore, propulsion lines and tanks must be protected from freezing to correctly operate. This occurs also to the Docking I/F and the Refueling I/F. As explained in paragraph 4.2.6, sensors provides temperature measurements to TCS

	PPU	Thrustor Units	Fuel Tanks	Feeding System	Orbit Sensors	Attitude Sensors	AOCS Actuators	AOCS OBC	Solar Arrays	Batteries	PCDU	Heat Pipes	MLI Blankets	Radiators	Electrical Heaters	TCS OBC	Temperature Sensors	Radiation Shields	MDPS Panels	Primary Structure	Secondary Structure	Docking I/F	Grasping I/F	Fluid Plane	Fluid Couplings	Electrical Connector	Refueling Valves	Refueling Tank	Commands Decoder	OBC	Data Storage Unit	RIU	Antennas	Receiver	Transmitter	Auto-tracking equipment	Data Bus	Electric Power Harness	
PPU																																							
Thrustor Units	X																																						
Fuel Tanks																																							
Feeding System		X	X																																				
Orbit Sensors																																							
Attitude Sensors																																							
AOCS Actuators																																							
AOCS OBC																																							
Solar Arrays																																							
Batteries																																							
PCDU	X				X	X	X		X	X																													
Heat Pipes	X				X	X					X	X																											
MLI Blankets			X	X																																			
Radiators														X																									
Electrical Heaters		X	X	X	X	X	X																																
TCS OBC																																							
Temperature Sensors	X	X	X	X	X	X	X		X	X	X																												
Radiation Shields	X									X	X																												
MDPS Panels																																							
Primary Structure		X	X				X							X																									
Secondary Structure	X			X	X	X			X	X	X	X	X	X	X	X	X	X																					
Docking I/F														X																									
Grasping I/F														X																									
Fluid Plane																																							
Fluid Couplings																																							
Electrical Connector																																							
Refueling Valves																																							
Refueling Tank			X																																				
Commands Decoder																																							
OBC							X			X	X			X	X	X	X	X																					
Data Storage Unit											X	X																											
RIU	X			X	X	X	X			X	X																												
Antennas																																							
Receiver																																							
Transmitter																																							
Auto-tracking equipment							X				X	X																											
Data Bus	X			X	X	X	X	X			X																												
Electric Power Harness	X	X			X	X	X	X	X	X	X																												

Figure 4.22: ICV global Connection Matrix

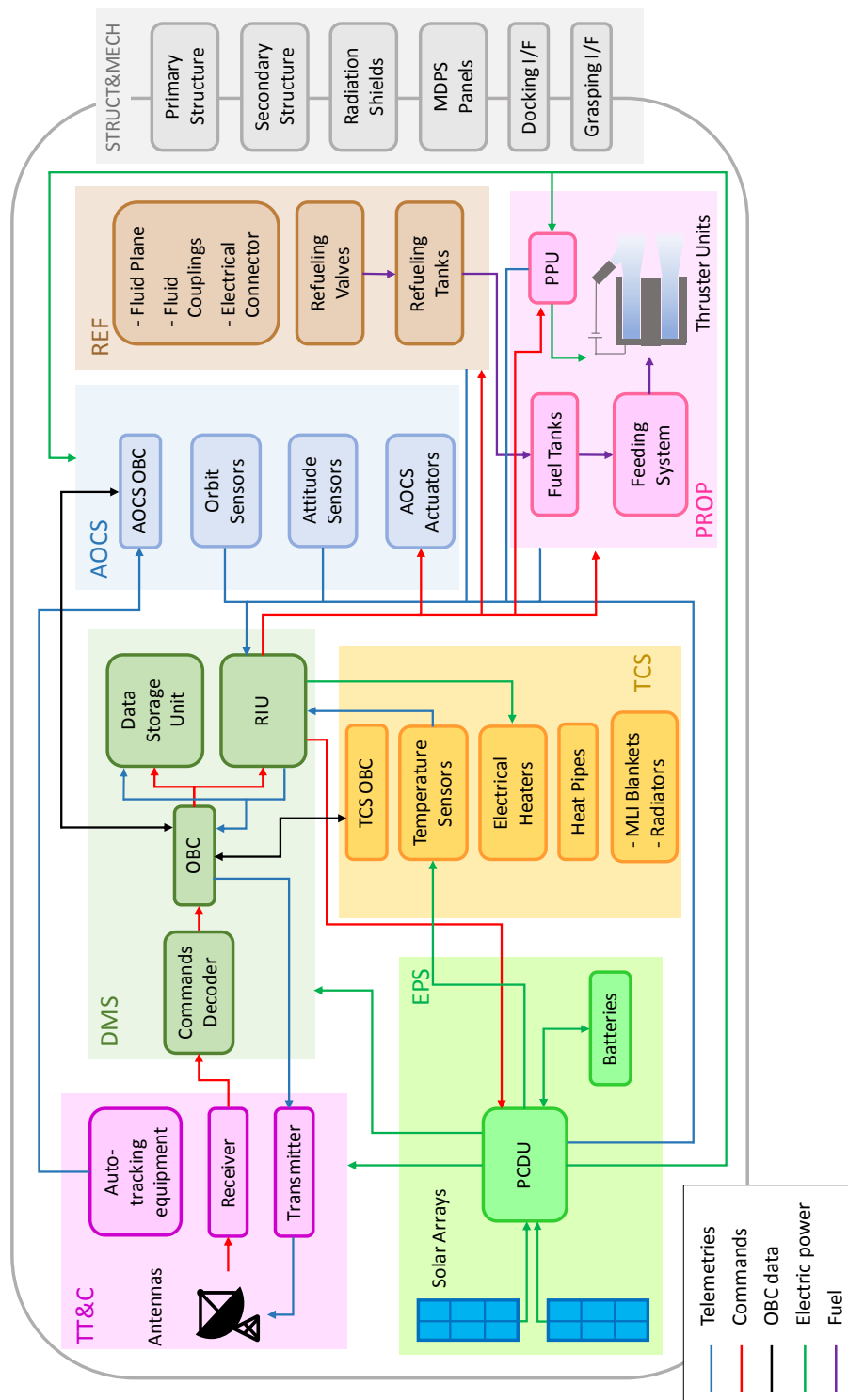


Figure 4.23: Global Functional Block Diagram

OBC, that consequently command Electrical Heaters to adjust the temperature, supplying or dissipating heat.

Thermal connections have been also identified for Orbit and Attitude Sensors. AOCS sensors on board spacecraft commonly are sun sensors, star sensors and magnetometers. The first two are optical devices, thus they produce heat that shall be transferred away through Heat Pipes. On the contrary, magnetometers need to be heated, often up to 100°C, to be operated. Heat Pipes interface with batteries and electronic components, since they dissipate heat and need rejection of this heat for their optimum and reliable operations. Between them, the PCPU is usually one of the most dissipative unit.

The PCPU is connected to all electrical devices, to which it provides electric power. Some kinds of AOCS actuators also needs electric supply, like control moment gyros, reaction wheels and momentum wheels, since they are all controlled by motors. Batteries and solar arrays are connected with the PCPU as explained in paragraph 4.2.3.

MLI Blankets interface with the Fuel Tanks and the Feeding system, since they are typically used to isolate propellant tanks and lines. They also cover great part of the Primary Structure. The Primary Structure mechanically interface with the major equipment, such as Thruster Units, the Fuel Tanks and the AOCS Actuators. Other components are mounted on the Secondary Structure, as well as the appendages like solar arrays and antennas.

The AOCS OBC and the TCS OBC interface with the OBC, because they are considered integrated in the OBC, which represent the central processor of the ICV.

4.2.11 Physical Block Diagram

Besides the Functional Block Diagram of Figure 4.23, a second block diagram has been developed. In this case the functional connections are indicated within a configuration more similar to a physical arrangement. In fact, there are components that present functional differences but that physically correspond. On the contrary, there are elements that coincide from a functional point of view but are physically separated. The Physical Block Diagram in Figure 4.24 takes into account these considerations and provides an alternative but also complementary point of view on the functional architecture. Among the main differences from the previous block diagram, it can be noticed that AOCS actuators have been distinguished in Attitude Control Actuators and in Orbital Control Actuators. Attitude Control Actuators include reaction wheels, momentum wheels and control moment

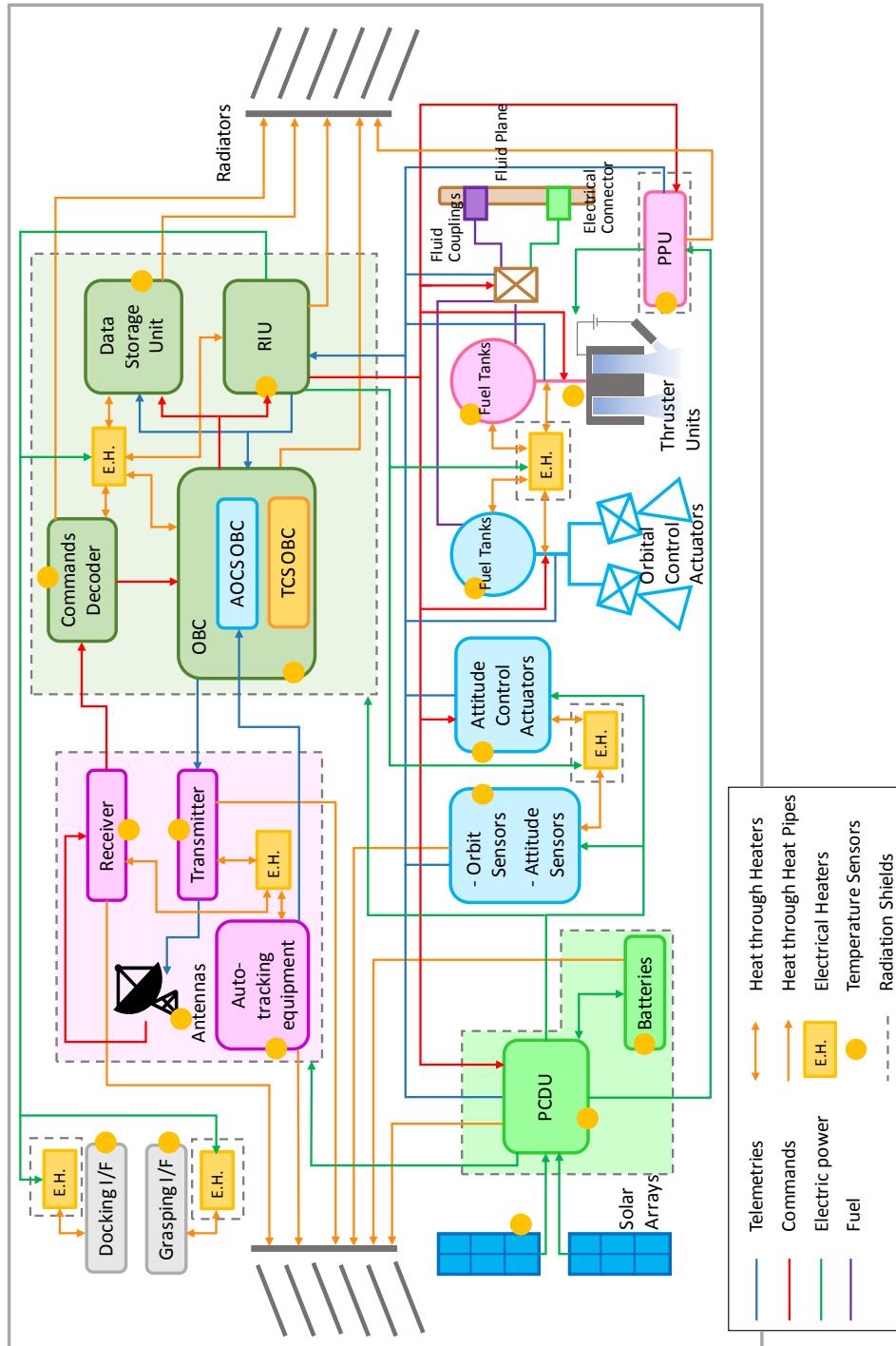


Figure 4.24: Physical Block Diagram

gyros, while Orbital Control Actuators are chemical thrusters and are more properly located in the PROP subsystem from a physical point of view. These latter are used for the rendezvous and mating operation with other on-orbit systems as will be described in the Modes of Operations analysis in Chapter 5. They are also used for the desaturation of the wheels when wheels become incapable of providing more torque on their axes.

Temperature Sensors and Electrical Heaters are not illustrated in a separated subsystem as they are in the Functional Block Diagram. They are instead shown near the elements that shall be monitored and the heat connections are also indicated. One-way arrows represent heat that is transferred through Heat Pipes from component to Radiators. Two-way arrows indicates the heat that is exchanged between Electrical Heaters and components.

The TCS OBC and the AOCS OBC have different functions from the OBC, and, from a functional perspective, they are included in two different subsystems. Nevertheless, they are integrated in the central processor and are positioned in the DMS subsystem. Similarly, Fuel Tanks and Refueling Tanks coincide in the physical arrangement, but they are associated with two different functions of the developed Functional Tree.

Chapter 5

Concept of Operations

The Concept of Operations (ConOps) describes how the system will be operated during all various life-cycle phases to meet stakeholder expectations. The ConOps is an important design tool able to capture both system requirements and architecture features, including some of which might be overlooked otherwise. Because it represents a crucial point in the mission definition and system design, the ConOps analysis must be carried on since the early design phases. Moreover, it serves as basis for subsequent definition documents such as the operations plan, Launch and Early Orbit Phase (LEOP) plan, and operations handbook. It also provides the foundation for the long-range operational planning activities, e.g. operational facilities, staffing, and network scheduling.

As introduced before, the ConOps analysis involves all the operations from the launch up to the disposal of the system at the End-of-Life (EOL). In particular, the mission definition is provided by the description of the major mission phases, the operational scenarios through the system traffic plan, the Design Reference Mission (DRM), which shows graphically the step-by-step sequence of the mission, each step corresponding to a different phase, the concerned orbit and the exploited infrastructures. It is an essential overview from launch to end of the mission, and the Phases Block Diagram (PBD) which shows conceptually the step-by-step sequence of the mission phases, illustrating the operational cycle of the ICV mission, main feature of this tool is to be able to emphasize the repetition of a phases cycle that is always the same as itself during the mission course. Analogously to the Function Analysis, the ConOps analysis is an iterative and recursive process, which shall be repeated until the desired level of detail is reached. In each stage of the design process, it is possible to define different type of requirements with different influences over the design [12, 14].

5.1 Scenarios Identification

Once the building blocks involved in the mission have been defined during the Functional Analysis, several scenarios and architectures have been identified and then compared among each other in order to select the optimal solution compliant with the mission statement, the stakeholders' needs and the requirements. Each of the identified scenarios has peculiar influences not only on the ICV functions and mission phases, but also on the features of the other orbital elements the ICV shall interface with. The ICV mission scenarios identified are the following:

- 2a)** The ICV performs Cargo Module docking at LOP-G docking port. After that, the ICV undocks and moves to the ORS where it interface with ORS nozzle tool to allow the transfer of propellant to the ICV tanks. Meanwhile cargo handling is carried out at the LOP-G. Once refueling operations have been completed, ICV moves back to the LOP-G where it docks with the Cargo Module. Then the ICV is ready for undocking and departure from LOP-G.
- 2b)** The ICV reaches the refueling orbit to docks with the ORS where refueling is performed through a refueling arm. Once refueling has been completed, the ICV undocks from the ORS and moves to the LOP-G where it docks the Cargo Module at the docking port. Then the ICV performs a proximity maneuver to reach a second docking port where the new Cargo Module has been prepared. After attaching the Cargo Module, the ICV is ready for undocking and departure procedures.
- 2c)** The ICV reaches the refueling orbit to docks with the ORS where refueling is performed through a tool that passes throughout the Cargo Module. Once refueling has been completed, the ICV undocks from the ORS and moves to the LOP-G where it docks the Cargo Module at the docking port. The ICV remains docked with the Cargo Module while cargo handling is being performed. Once the Cargo Module has been prepared, the ICV is ready for undocking and departure procedures.
- 2d)** The ICV performs Cargo Module docking at LOP-G docking port. After that, the ICV is grabbed by a LOP-G robotic arm in order to be moved to a second docking port where the new Cargo Module has been prepared. After attaching the Cargo Module, the ICV undocks and moves to the ORS where refueling is performed through a tool that passes throughout the Cargo Module. Once refueling operations have been exploited, the ICV is ready for undocking and departure procedures.

Among these scenarios, a preliminary trade-off analysis has been performed in order to point out the most suitable solutions according to the following Figures of Merits (FoM):

- *Docking operations*: number of docking maneuvers required in the scenario. Increased number of docking maneuvers involves the rise in risk of collision with the station;
- *Berthing operations*: number of relocations through berthing maneuvers. Decreased risk of collision with the station and reduction in fuel consumption;
- *Proximity maneuvers*: number of relocations without robotic arm. Increased risk of collision with the station and rise in fuel consumption;
- *Refueling Operations*: Direct refueling interface, increased system reliability and reduction in mission complexity. Refueling through refueling arm, inadequate knowledge about this kind of technology and absence of past applications. Refueling through Cargo Module, greater knowledge about this kind of technology and presence of past similar applications;
- *Waiting during cargo handling*: time of inactivity docked to LOP-G. Increased inactivity time involves the rise in mission duration;
- *New Cargo Module*: Cargo Module changing. Increased number of available Cargo Modules involves the reduction in mission duration;
- *Transfers*: number of transfer in a single and-to-end mission. Increased number of transfers involves the rise in mission duration, in risk of collision with the station and in propellant consumption;

The Figures of merits presented above, since they all strongly influence the scenario, have all the same weight equal to 1. Each of these FOMs may be present or not present in the scenario, therefore, we have chosen to attribute score 1 in the event that the FOM is present and score 0 if it is absent. The exceptions are represented by *Docking operations*, which is evaluated with a numbering directly proportional to the count of docking maneuvers present in a single end-to-end mission and normalized to 1 (maximum number of docking operations is 4 in scenarios 2a and 2b, all the others scenarios present only 3 docking maneuvers, so the final value for each scenario is obtained by dividing the number of docking maneuvers by 4), by *Refueling operations*, which is evaluated directly proportional to the king of refueling maneuvers present in a single end-to-end mission and normalized to 1 (maximum value is 1 in scenario 2a because it present direct

refueling operations, 0.5 for scenarios that present refueling through Cargo Module and -0.5 for scenarios that present the use of refueling arm) and by *Transfers*, which is evaluated with a numbering directly proportional to the count of transfers present in a single end-to-end mission and normalized to 1 (maximum number of transfers is 4 in scenarios 2a, all the others scenarios present only 3 transfers, so the final value for each scenario is obtained by dividing the number of transfers by 4).

Berthing operations and *New Cargo Module* are Figures of merit whose presence is positively evaluated as they increase the reliability degree of the mission. On the other hand, *Proximity maneuvers*, *Waiting during cargo handling*, *Transfers* and *Docking operations* are Figures of merit whose presence is negatively evaluated as they decrease the mission reliability degree.

The results of the analysis are shown in Table 5.1.

	2a	2b	2c	2d
Docking operations	1	1	0.75	0.75
Berthing operations	0	0	0	1
Proximity maneuvers	0	1	0	0
Refueling operations	1	0.5	0.5	0.5
Waiting during cargo handling	0	0	1	0
New Cargo Module	0	1	0	1
Transfers	1	0.75	0.75	0.75
Total Score	-1	-2.25	-2	1

Table 5.1: Scenarios identification

As shown in Table 5.1, scenarios 2a and 2d provide solutions more reliable rather than scenarios 2b and 2c. Hence, these selected scenarios will be analyzed in detail in the next Section whereas, from a functional point of view, the corresponding platforms have been presented in 4

5.2 ICV Basic Configurations

ICV is exploited for cargo transportation mission, so, the spacecraft can assume two main configurations based on the Cargo Module. A conceptual and basic system design has been developed. In this section only the system-level configuration is considered, all the configurations at subsystem level are referred to the subsequent Section 5.5 concerning the Modes of Operations.

- *Not loaded*, in this configurations the Cargo Module is not attached to ICV and the docking interface is able to dock directly with the LOP-G docking ports (e.g. refueling docking port). The Figure 5.1 shows the placement of the solar arrays, the position of the main HETs and the position of the docking interface.

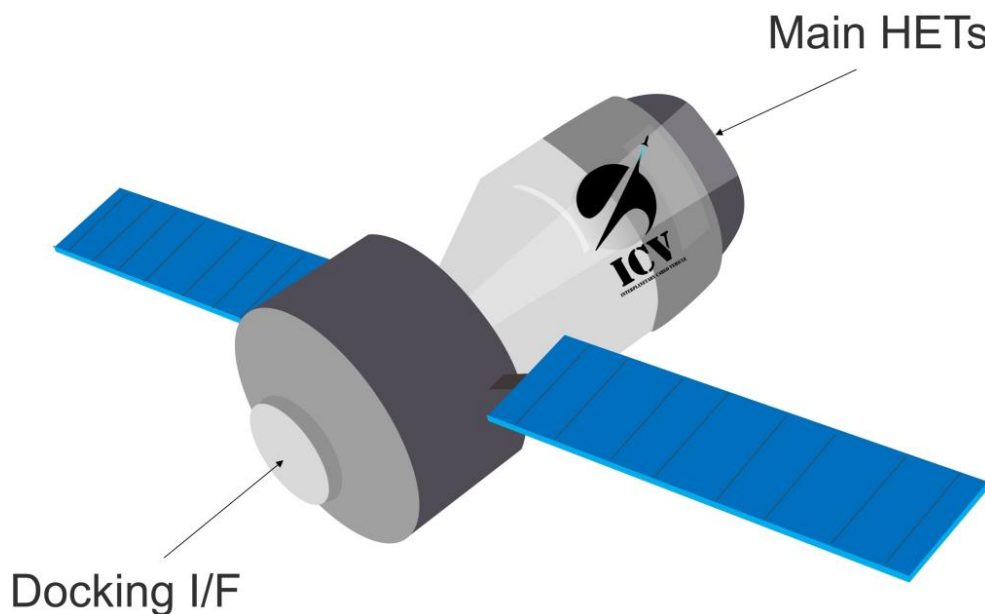


Figure 5.1: Not loaded configuration

- *Loaded*, in this configurations the Cargo Module is attached to ICV. The only docking interface able to dock directly with the LOP-G docking port is the Cargo Module one. The Figure 5.2 shows the placement of the Cargo Module and the positions of the relative docking interfaces.

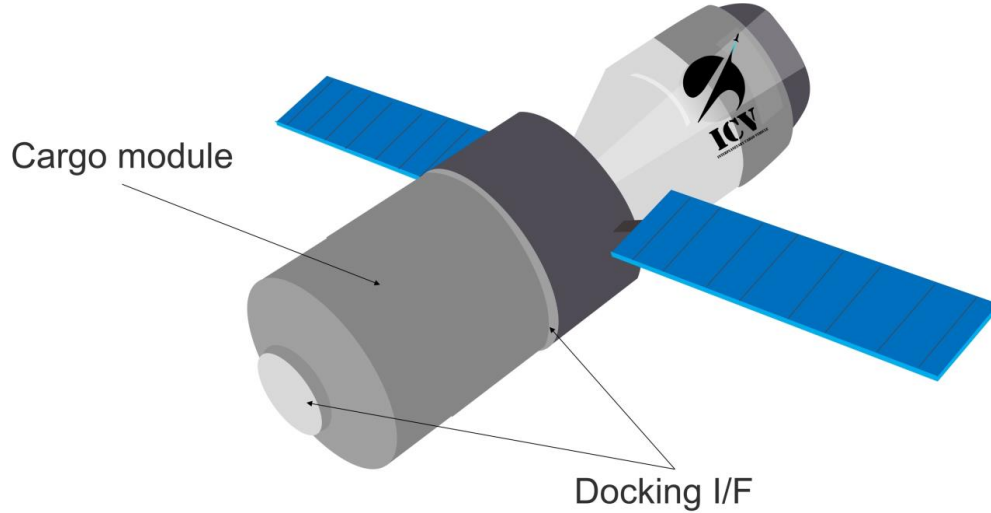


Figure 5.2: Loaded configuration

5.3 Mission Phases

The first ConOps step consists of identifying the high-level mission phases, shared among both selected scenarios, and characterized them through their peculiar features and properties. Then, the two scenarios are graphically represented in their preliminary DRM and corresponding PBD which allow to obtain a more clear and intuitive idea of the mission [17].

5.3.1 Preliminary Mission Phases Identification

As anticipated before, each scenario can be split in several phases, each one characterized by a well precise state of the system defined by the external environment (natural and induced environments, e.g. radiation, electromagnetic, heat, vibration and contamination environment) within which the system operates. The transition between one state of the system to the next one corresponds also to the transition between two phases. Hence, each mission phase is therefore characterized by a specific orbit and environment, in terms of loads, available resources,

external temperatures and pressure, radiation. Accordingly to the considerations made above, the whole mission has been split into fifteen phases. Below we have characterized them from an operational point of view.

1. *Launch:*
all the operations required to put, through a launcher, the ICV into LEO.
2. *Early operations:*
all the operations needed to check the subsystems.
3. *EOR to LOP-G:*
the electric orbit raising from LEO to LOP-G orbit.
4. *Rendezvous and mating with LOP-G from Earth orbit:*
all the operations requested in the LOP-G vicinity to attach ICV with LOP-G from Earth orbit.
5. *Logistics, checking and maintenance:*
all the operations requested to guarantee the proper operation of the ICV and the maintenance operations of the whole system.
6. *Cargo handling at LOP-G:*
all the operations needed to deliver and retrieve the cargo module according to the mission requests.
7. *Unmating from LOP-G:*
all the operations needed to detach ICV from LOP-G.
8. *LOP-G – ORS EOR:*
the electric orbit raising requested to reach the ORS orbit from LOP-G orbit.
9. *Rendezvous and mating with ORS:*
all the operations requested in the ORS vicinity to attach ICV with ORS.
10. *Refueling:*
all the operations requested to accomplish the ICV refueling.
11. *Unmating from ORS:*
all the operations needed to detach ICV from ORS.
12. *ORS – MOS EOR:*
the electric orbit raising requested to reach the MOS orbit from ORS orbit.

13. *Rendezvous and mating with MOS:*
all the operations requested in the MOS vicinity to attach ICV with MOS from deep space.
14. *Logistics and checking:*
all the operations requested to guarantee the proper operation of the ICV.
15. *Cargo handling at MOS:*
all the operations needed to deliver and retrieve the cargo module according to the mission requests.
16. *Unmating from MOS:*
all the operations needed to detach ICV from MOS.
17. *MOS – LOP-G EOR:*
the electric orbit raising requested to reach the LOP-G orbit from MOS orbit.
18. *Rendezvous and mating with LOP-G from deep space:*
all the operations requested in the LOP-G vicinity to attach ICV with LOP-G from Earth orbit.

At this point of the analysis, the phases relating to the disposal do not yet appear since they are introduced only afterwards following the refinement related to each scenario.

Table 5.2 and Table 5.3 provide the main features of each phase in terms of starting and ending events, initial orbit, final orbit, phase description, environment and Cargo Module configuration. In addition, a color coding has been used to facilitate understanding of the surrounding environment. In detail, each color corresponds to a faced environment: green for Earth orbit/cislunar space, grey for Lunar orbit, light blue for Deep space and Orange for Mars orbit.

No.	Phase	Start	End	Initial orbit	Final orbit	Description	Environment	Cargo module configuration
1.	Launch	Lift-off	Separation from launcher	Ground	LEO	ΔV provided by the launcher	Payload envelope	Not loaded
2.	Early operations	Separation from launcher	ICV ready for EOR	LEO	LEO	Operations needed to check the ICV subsystems	Earth orbit	Not loaded
3.	EOR to LOP-G	ICV ready for EOR	ICV arrival in the proximity of LOP-G	LEO	LOP-G orbit	LEO to LOP-G EOR	Cis-lunar	Not loaded
4.	Rendezvous and mating with LOP-G from Earth orbit	ICV arrival in the vicinity of LOP-G	ICV attached to LOP-G	LOP-G orbit	LOP-G orbit	Operations requested in the LOP-G vicinity to attach ICV with LOP-G from Earth orbit	Lunar orbit	Not loaded
5.	Logistics, checking and maintenance	ICV attached to LOP-G	ICV ready for cargo handling	LOP-G orbit	LOP-G orbit	Operations requested to guarantee the proper operation of the ICV and the maintenance operations of the whole system	Lunar orbit	Not loaded
6.	Cargo handling at LOP-G	ICV ready for cargo handling	Cargo module managed on ICV	LOP-G orbit	LOP-G orbit	Operations needed to deliver and retrieve the cargo module according to the mission requests	Lunar orbit	Loaded
7.	Unmating from LOP-G	Cargo module managed and ICV ready for detachment	ICV detached from LOP-G	LOP-G orbit	LOP-G orbit	Operations needed to detach ICV from LOP-G	Lunar orbit	Loaded
8.	LOP-G – MOS EOR	ICV detached from LOP-G	ICV arrival in the vicinity of ORS	LOP-G orbit	ORS orbit	Electric orbit raising requested to reach the ORS orbit	Lunar orbit	Loaded
9.	Rendezvous and mating with ORS	ICV arrival in the vicinity of ORS	ICV attached to ORS	ORS orbit	ORS orbit	Operations requested in the ORS vicinity to attach ICV with ORS	Lunar orbit	Loaded
10.	Refueling	ICV attached to ORS	ICV refueled and ready for detachment	ORS orbit	ORS orbit	Operations requested to accomplish the ICV refueling	Lunar orbit	Loaded

Table 5.2: Table of phases (first part)

11.	Unmating from ORS	ICV refueled and ready for detachment	ICV detached from ORS	ORS orbit	ORS orbit	Operations needed to detach ICV from ORS	Lunar orbit	Loaded
12.	LOP-G – MOS EOR	ICV detached from LOP-G	ICV arrival in the vicinity of MOS	ORS orbit	MOS orbit	Electric orbit raising requested to reach the MOS orbit	Deep space	Loaded
13.	Rendezvous and mating with MOS	ICV arrival in the vicinity of MOS	ICV attached to MOS	MOS orbit	MOS orbit	Operations requested in the MOS vicinity to attach ICV with MOS	Mars orbit	Loaded
14.	Logistics and checking	ICV attached to MOS	ICV ready for cargo handling	MOS orbit	MOS orbit	Operations requested to guarantee the proper operation of the ICV	Mars orbit	Loaded
15.	Cargo handling at MOS	ICV ready for cargo handling	Cargo module managed and ICV ready for detachment	MOS orbit	MOS orbit	Operations needed to deliver and retrieve the cargo module according to the mission requests	Mars orbit	Loaded
16.	Unmating from MOS	Cargo module managed and ICV ready for detachment	ICV detached from MOS	MOS orbit	MOS orbit	Operations needed to detach ICV from MOS	Mars orbit	Loaded
17.	MOS – LOP-G EOR	ICV detached from MOS	ICV arrival in the vicinity of LOP-G	MOS orbit	LOP-G orbit	Electric orbit raising requested to reach the LOP-G orbit	Deep space	Loaded
18.	Rendezvous and mating with LOP-G from deep space	ICV arrival in the vicinity of LOP-G	ICV attached to LOP-G	LOP-G orbit	LOP-G orbit	Operations requested in the LOP-G vicinity to attach ICV with LOP-G from deep space	Lunar orbit	Loaded

Table 5.3: Table of phases (second part)

5.3.2 Environmental Requirements

New requirements arise from the analysis of the mission phases: they are the *Environmental Requirements*. As described at the beginning of this section, each mission phase is characterized by a specific environment, both natural and induced. Environmental Requirements, thus, focuses on natural and induced conditions that constrain the ICV's features. In Table 5.4 some examples are indicated for two different mission phases.

Launch	<i>The ICV shall withstand launch environment during launch;</i>
	<i>The ICV shall be able to sustain launch loads during launch;</i>
	<i>The ICV shall be able to sustain launch vibration during launch;</i>
	<i>The ICV shall limit heat leak/gain to/from natural environment during launch;</i>
	<i>The ICV shall withstand TBD temperature range during launch;</i>
	<i>ICV shall be able to sustain separation shock during launch.</i>
EOR to LOP-G	<i>The ICV shall withstand EOR environment during EOR from LEO to LOP-G;</i>
	<i>ICV shall be able to sustain operational loads during EOR from LEO to LOP-G;</i>
	<i>The ICV shall limit heat leak/gain to/from natural environment during EOR from LEO to LOP-G;</i>
	<i>The ICV shall be able to operate within TBD temperature range during EOR from LEO to LOP-G;</i>
	<i>The ICV shall be able to sustain a TBD radiation dose during EOR from LEO to LOP-G;</i>

Table 5.4: Examples of *Environmental Requirements* for the *Launch* phase and the *EOR to LOP-G* phase

Requirements driving components sizing can be established if environmental requirements from all phases are taken into account. For example, considering radiation dose from the various environments, the total radiative dose that radiation shields have to counteract can be fixed. This total dose would drive the radiation shields sizing.

5.3.3 Preliminary Design Reference Mission (DRM)

Like any other space mission, the ICV mission begins with the launch. Once the desired Earth orbit is reached, ICV is released by the launcher and the preliminary operations begin. These kind of operations continue until the proper functioning of the spacecraft has been tested. Once the Ground Station clearance is obtained, the first electric orbit rising is performed in order to reach the LOP-G orbit. At the end of the orbital transfer, when ICV reaches 30 km from the station, the rendezvous and mating phase is accomplished. At this time ICV is docked to LOP-G. Subsequently, the maintenance, control, logistics, and cargo handling phases are carried out in sequence. After have accomplished all these operations, the spacecraft separates from the station and starts the second electric orbit rising with the aim of reaching the ORS orbit. At the end of the orbital transfer, when ICV reaches 5 km from the ORS, the rendezvous and mating phase is performed. At this time ICV is docked to LOP-G and refueling phase is carried out. After have accomplished the refueling operations, the spacecraft separates from the station and starts the third electric orbit rising with the aim of reaching the MOS orbit. At the end of the deep space transfer, when ICV reaches 30 km from the MOS, the rendezvous and mating phase is performed. In Martian orbit, while docked to MOS, the control, logistics and cargo handling phases are carried out in sequence. After have accomplished all these operations, the spacecraft separates from the station and starts the fourth electric orbit rising in order to return in the LOP-G orbit. Once the station orbit is reached, the rendezvous and mating from deep phase is accomplished and the mission cycle can proceed. In Figure 5.3 is shown the related DRM.

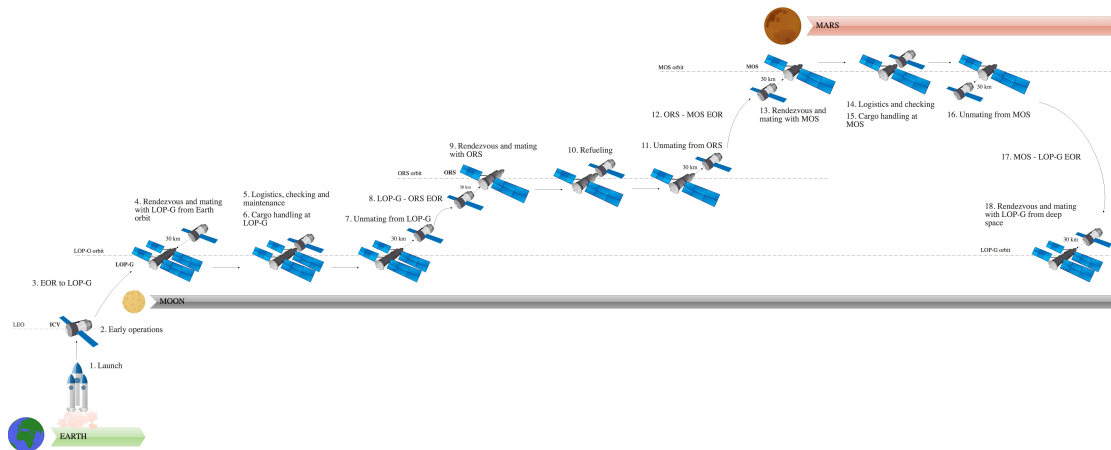


Figure 5.3: Design Reference Mission

5.3.4 Preliminary Phases Block Diagram (PBD)

The Phases Block Diagram shows the different parts of the mission. The first part of the diagram represents all the phases necessary to start the effective operating cycle and it is constituted by phases 1,2,3 and 4. The second part of the diagram represents all the phases necessary to perform the effective operating cycle of the transportation mission, it is constituted by phases 5 to 18 (phases 8 to 11 represent the refueling operations). These ones are repeated identically until the end of the mission.

A color coding has been used to facilitate understanding of the blocks. In detail, each color corresponds to a reached orbit: green for Earth orbit/cislunar space, grey for Lunar orbit, light blue for Deep space and Orange for Mars orbit. In addition, a stream of arrows guides the succession of the different phases. In Figure 5.4 is shown the relative PBD.

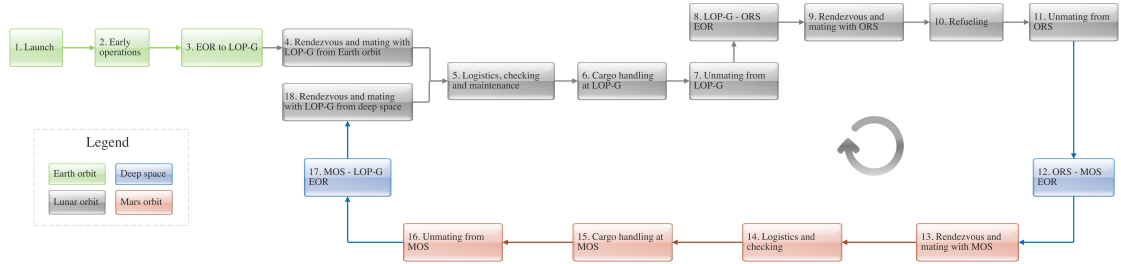


Figure 5.4: Phases Block Diagram

5.4 Mission Phases Refinement

The second ConOps step consists of identifying the lower-level mission phases, specified for each selected scenarios, and characterized them through their peculiar features and properties. Then, the two scenarios are graphically represented to their complete DRM and corresponding PBD which allow to obtain a more clear and intuitive idea of the whole mission.

5.4.1 Mission Phases Specification for Scenario 2a

In this section, the phases identified previously in Section 5.3.1 have been studied in detail for Scenario 2a. In particular, only the phases with significant differences from the previous version are reported and specified. During the the

mission study, we have chosen to always perform docking maneuvers as mating operations because of MOS is not equipped with a robotic arm capable of performing berthing operations. Below, the phases characterization from operational point of view.

- *Launch, Early operations* and *EOR to LOP-G* are the same as the previous identified.
- 4 *Rendezvous and docking with ORS:*
all the operations required in ORS vicinity to dock ICV to ORS refueling docking port.
- 5 *Refueling:*
all the operations required to transfer fuel to ICV tank.
- 6 *Undocking from ORS:*
all the operations required to undock Cargo module from ORS.
- 7 *EOR to LOP-G:*
the electric orbit raising from ORS to LOP-G orbit.
- 8 *Rendezvous and docking with Cargo module:*
all operations required in LOP-G vicinity to dock ICV to Cargo module docking port.
- 9 *Undocking from LOP-G:*
all the operations required to undock Cargo module from LOP-G.
- *LOP-G – MOS EOR, Rendezvous and docking with MOS, Checking and Cargo handling at MOS, Undocking from MOS* and *MOS – LOP-G EOR* are the same as the previous identified.
- 15 *Rendezvous and docking with LOP-G:*
all the operations required in the LOP-G vicinity to dock Cargo module to LOP-G docking port.
- 16 *Logistics, checking and maintenance:*
all the operations required to verify and guarantee the proper functioning of ICV.
- 17 *Undocking from Cargo module:*
all operations required to undock ICV from Cargo module.

- 18 *EOR to ORS (from LOP-G orbit):*
the electric orbit raising from LOP-G to ORS orbit.

In addition, the disposal operations have been inserted at the end of the operational life of the ICV. The end-of-life is represented by the system switch-off once reached the assigned graveyard orbit. The phases that represent the *Disposal* are:

- D1** *EOR to graveyard orbit and switch-off:*
the electric orbit raising from LOP-G orbit to graveyard orbit and system shutdown.

As explained in the Section 5.3.1, Table 5.5 and Table 5.6 provide the main features of each phase in terms of starting and ending events, initial orbit, final orbit, phase description, environment and Cargo Module configuration. In addition, a color coding has been used to facilitate understanding of the surrounding environment. In detail, each color corresponds to a faced environment: green for Earth orbit/cislunar space, grey for Lunar orbit, light blue for Deep space and Orange for Mars orbit.

In Table 5.5 and Table 5.6 all the phases are shown in order to provide an overview of the whole scenario.

No.	Phase	Start	End	Initial orbit	Final orbit	Description	Environment	Cargo module configuration
1.	Launch	Lift-off	Orbit insertion	Ground	LEO	Operations required to put into LEO the ICV through a launcher	Payload envelope	Not loaded
2.	Early operations	Orbit insertion	ICV ready for EOR	LEO	LEO	Operations required to check the subsystems health status	Earth orbit	Not loaded
3.	EOR to ORS	ICV ready for EOR	ICV arrival in ORS refueling docking port vicinity	LEO	ORS orbit	Electric orbit raising from LEO to ORS orbit	Cis-lunar	Not loaded
4.	Rendezvous and docking with ORS	ICV arrival in ORS refueling docking port vicinity	ICV docked to ORS refueling docking port	ORS orbit	ORS orbit	Operations required in ORS vicinity to dock ICV to LOP-G refueling docking port	Lunar orbit	Not loaded
5.	Refueling	ICV docked to ORS refueling docking port	ICV refueled	ORS orbit	ORS orbit	Operations required transfer fuel to ICV tank	Lunar orbit	Not loaded
6.	Undocking from ORS	ICV refueled	ICV undocked from ORS	ORS orbit	ORS orbit	Operations required to undock ICV from ORS	Lunar orbit	Not Loaded
7.	EOR to ORS	ICV undocked from ORS	ICV arrival in LOP-G vicinity	ORS orbit	LOP-G orbit	Electric orbit raising from ORS to LOP-G orbit	Lunar orbit	Not loaded
8.	Rendezvous and docking with Cargo module	ICV arrival in LOP-G vicinity	ICV docked to Cargo module docking port	LOP-G orbit	LOP-G orbit	Operations required in LOP-G vicinity to dock ICV to Cargo module docking port	Lunar orbit	Not loaded
9.	Undocking from LOP-G	ICV docked to Cargo module docking port	Cargo module undocked from LOP-G	LOP-G orbit	LOP-G orbit	Operations required to undock Cargo module from LOP-G	Lunar orbit	Loaded
10.	LOP-G – MOS EOR	Cargo module undocked from LOP-G	ICV arrival in MOS vicinity	LOP-G orbit	MOS orbit	Electric orbit raising required to reach the MOS orbit	Deep space	Loaded
11.	Rendezvous and docking with MOS	ICV arrival in MOS vicinity	Cargo module docked to MOS	MOS orbit	MOS orbit	Operations required in MOS vicinity to dock Cargo module with MOS	Mars orbit	Loaded

Table 5.5: Table of phases **2a** (first part)

12.	Checking and Cargo handling at MOS	Cargo module docked to MOS	Cargo module managed and ready for undocking	MOS orbit	MOS orbit	Operations required to verify the proper functioning of ICV and to deliver/retrieve cargo assets	Mars orbit	Loaded
13.	Undocking from MOS	Cargo module managed and ready for undocking	Cargo module undocked from MOS	MOS orbit	MOS orbit	Operations required to undock Cargo module from MOS	Mars orbit	Loaded
14.	MOS – LOP-G EOR	Cargo module undocked from MOS	ICV arrival in LOP-G vicinity	MOS orbit	LOP-G orbit	Electric orbit raising required to reach the LOP-G orbit	Deep space	Loaded
15.	Rendezvous and docking with LOP-G	ICV arrival in LOP-G vicinity	Cargo module docked to LOP-G	LOP-G orbit	LOP-G orbit	Operations required in LOP-G vicinity to dock Cargo module to LOP-G docking port	Lunar orbit	Loaded
16.	Logistics, checking and maintenance	Cargo module docked to LOP-G	ICV ready for refueling operations	LOP-G orbit	LOP-G orbit	Operations required to verify and guarantee the proper functioning of ICV	Lunar orbit	Loaded
17.	Undocking from LOP-G	ICV ready for refueling operations	ICV undocked from Cargo module	LOP-G orbit	LOP-G orbit	Operations required to undock ICV from Cargo module	Lunar orbit	Not Loaded
18.	EOR to ORS	ICV undocked from Cargo module	ICV arrival in ORS refueling docking port vicinity	LOP-G orbit	ORS orbit	Electric orbit raising from LOP-G to ORS orbit	Lunar orbit	Not loaded
D1.	EOR to graveyard orbit and switch-off	ICV undocked from Cargo module	ICV completely switched off	LOP-G orbit	Grave yard orbit	Electric orbit raising from LOP-G orbit to graveyard orbit and system shutdown	Cis-lunar	Not loaded

Table 5.6: Table of phases **2a** (second part)

5.4.2 Design Reference Mission - 2a

The extended launch phase (represented in Figure 5.5 by the Roman number "I") includes launch, early operations and EOR to ORS phases previously described in Section 5.3.3.

At this point, the extended operative phase (represented in Figure 5.5 by the Roman number "II") can begin. Subsequently, rendezvous and docking with ORS, refueling, undocking from ORS, EOR to LOP-G, rendezvous and docking with Cargo Module and undocking from LOP-G phases are carried out in sequence. After have accomplished all these operations, the spacecraft, with its cargo module, separates from the station and starts the third electric orbit rising with the aim of reaching the MOS orbit.

All the phases between the EOR to MOS orbit and the EOR returning to LOP-G orbit are the same as the previously described in Section 5.3.3.

Once the lunar station orbit is reached, the rendezvous and docking from deep phase is accomplished at the LOP-G docking port. After the logistic, checking and maintenance phase, ICV have to return in the refueling configuration. In order to ensure the correct procedure, undocking from LOP-G and EOR to ORS phases are carried out in sequence. In such a way the mission cycle can proceed until disposal.

The extended disposal phase (represented in Figure 5.6 by the Roman number "III"), which includes the EOR to graveyard orbit and system switch-off, represents the ICV end-of-life and the irreversible mission conclusion.

In Figure 5.5 and Figure 5.6 is shown the related DRM.

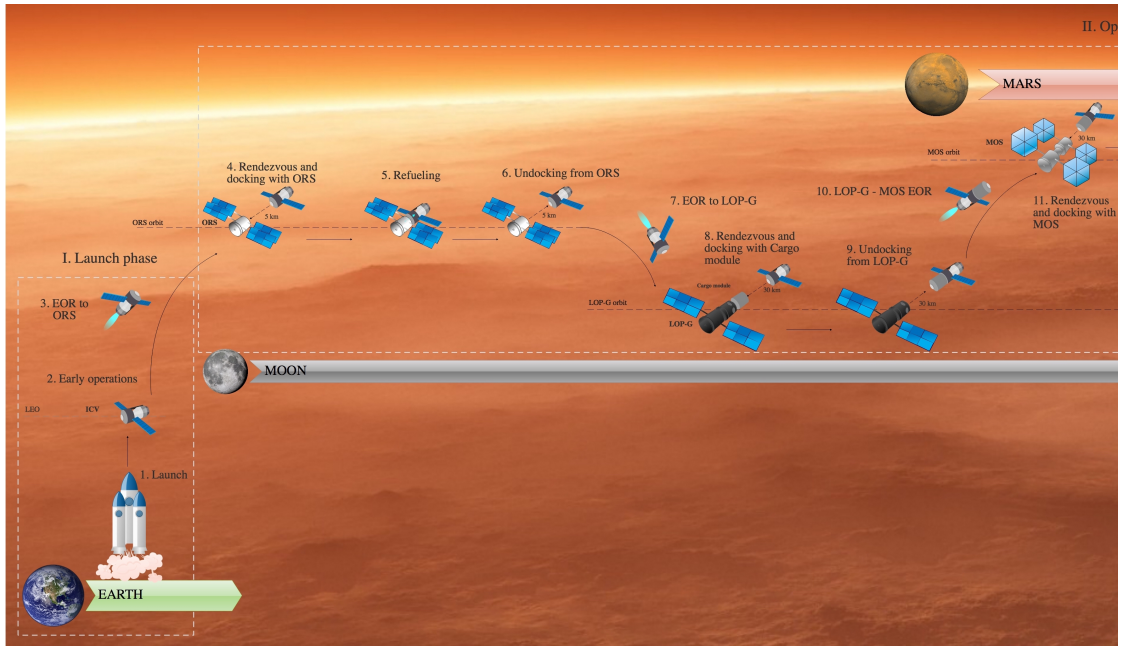


Figure 5.5: Design Reference Mission **2a** (first part)

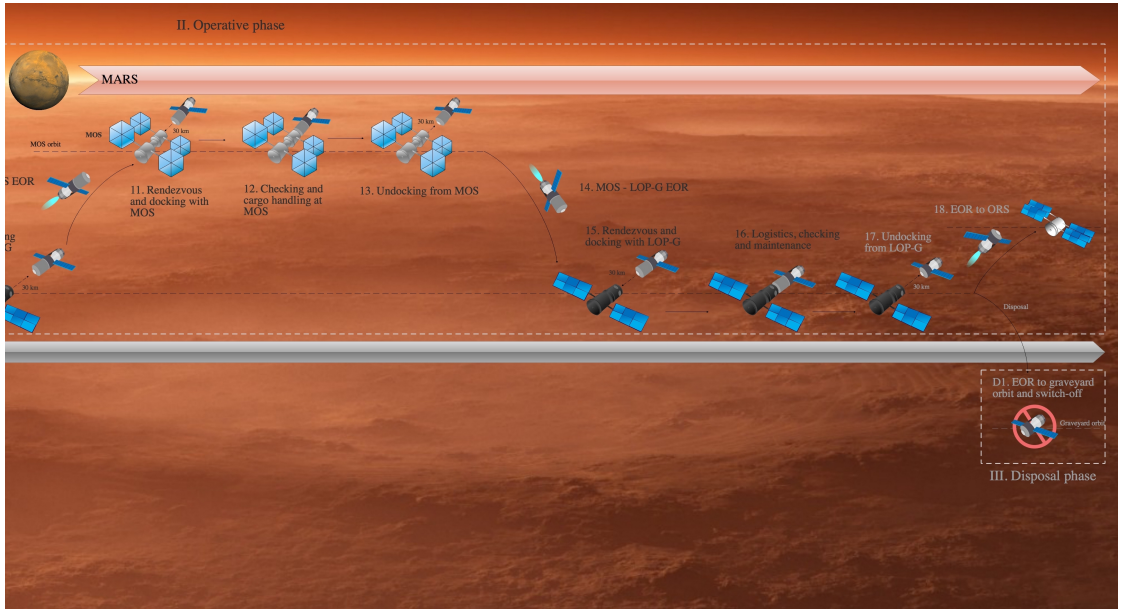


Figure 5.6: Design Reference Mission **2a** (second part)

5.4.3 Phases Block Diagram - 2a

The Phases Block Diagram shows the three main extended phases of the mission: launch, operative and disposal.

The first part of the diagram represents the launch phase, which is constituted by the phases necessary to start the effective operating cycle, that are phases 1,2 and 3.

The second part of the diagram represents the operational phase, which is constituted by the phases necessary to perform the effective operating cycle of the transportation mission, it is constituted by phases 4 to 19. These ones are repeated identically until the mission end.

The third part of the diagram represents the disposal phase, which is constituted by the phase necessary to perform the disposal and the end-of-life operations. It is constituted by phase D1.

As reported in the previous Section 5.3.4, a color coding has been used to facilitate understanding of the blocks. In detail, each color corresponds to a reached orbit: green for Earth orbit/cislunar space, grey for Lunar orbit, light blue for Deep space and Orange for Mars orbit. In addition, a stream of arrows guides the succession of the different phases. In Figure 5.7 is shown the relative PBD.

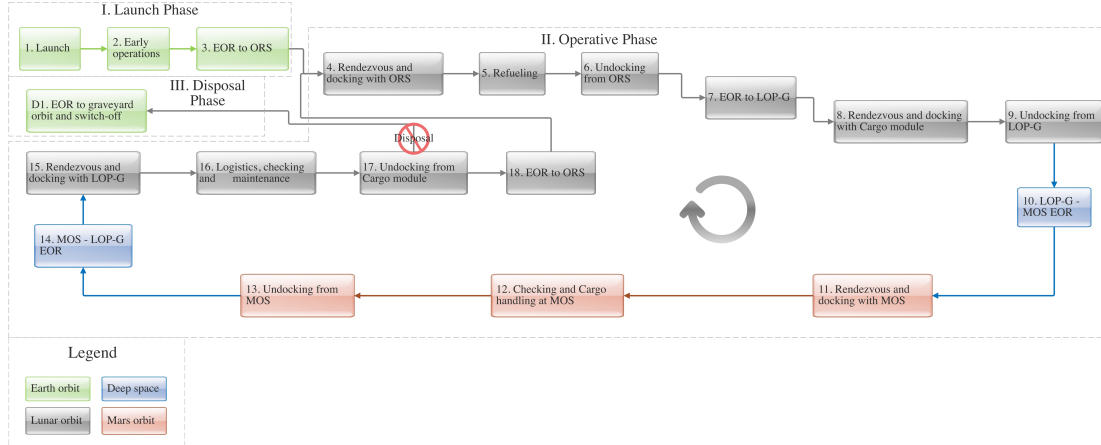


Figure 5.7: Phases Block Diagram 2a

5.4.4 Mission Phases Specification for Scenario 2d

In this section, the phases identified previously in Section 5.3.1 have been studied in detail for Scenario 2d. In particular, only the phases with significant differences from the previous version are reported and specified. In accordance with the considerations made about the Scenario 2a, we have chosen to always perform docking maneuvers as mating operations. Below, the phases characterization from operational point of view.

- *Launch, Early operations* and *EOR to LOP-G* are the same as the previous identified.
- 4 *Rendezvous and docking with Cargo module:*
all the operations required in LOP-G vicinity to dock ICV to Cargo module docking port. Cargo module is docked to LOP-G through the opposite docking port.
- 5 *Undocking from LOP-G:*
all the operations required to undock Cargo module from LOP-G.
- 6 *LOP-G – ORS EOR:*
the electric orbit raising required to reach the ORS orbit starting from LOP-G orbit.
- 7 *Rendezvous and docking with ORS:*
all the operations required in ORS vicinity to dock Cargo module to ORS refueling docking port.
- 8 *Refueling:*
all the operations required to transfer fuel to ICV tank throughout Cargo module.
- 9 *Undocking from ORS:*
all the operations required to undock Cargo module from ORS.
- *ORS – MOS EOR, Rendezvous and docking with MOS, Checking and Cargo handling at MOS, Undocking from MOS* and *MOS – LOP-G EOR* are the same as the previous identified.
- 15 *Rendezvous and docking with LOP-G:*
all the operations required in the LOP-G vicinity to dock Cargo module to LOP-G docking port.

- 16 *Logistics, checking and maintenance:*
all the operations required to verify and guarantee the proper functioning of ICV.
- 17 *Berthing and undocking:*
all the operations required to attach ICV grasping mechanism to LOP-G robotic arm and to undock ICV from Cargo module.
- 18 *Relocation to new Cargo module:*
mechanical displacement of the ICV, by means of LOP-G robotic arm, from old Cargo module docking port to new Cargo module docking port.
- 19 *Docking and release:*
all the operations required to dock ICV at new Cargo module docking port and to detach ICV grasping mechanism from LOP-G robotic arm.

In addition, the disposal operations have been inserted at the end of the operational life of the ICV. The end-of-life is represented by the system switch-off once reached the assigned graveyard orbit. The phases that represent the *Disposal* are:

- D1** *Undocking from Cargo module:*
the electric orbit raising from LOP-G orbit to graveyard orbit and system shutdown.
- D2** *EOR to graveyard orbit and switch-off:*
all the operations required to undock ICV from Cargo module.

For Table 5.7 and Table 5.8 are valid the same considerations made for the tables in Section ???. All the phases are shown in order to provide an overview of the whole scenario.

No.	Phase	Start	End	Initial orbit	Description	Environment	Cargo module configuration
1.	Launch	Lift-off	Orbit insertion	Ground	Operations required to put into LEO the ICV through a launcher	Payload envelope	Not loaded
2.	Early operations	Orbit insertion	ICV ready for EOR	LEO	Operations required to check the subsystems health status	Earth orbit	Not loaded
3.	EOR to LOP-G	ICV ready for EOR	ICV arrival in LOP-G vicinity	LEO	Electric orbit raising from LEO to LOP-G orbit	Cis-lunar	Not loaded
4.	Rendezvous and docking with Cargo module	ICV arrival in LOP-G vicinity	ICV docked to Cargo module docking port	LOP-G orbit	Operations required in LOP-G vicinity to dock ICV to Cargo module docking port	Lunar orbit	Not loaded
5.	Undocking from LOP-G	ICV docked to Cargo module docking port	Cargo module undocked from ICV	LOP-G orbit	Operations required to undock Cargo module from LOP-G	Lunar orbit	Loaded
6.	EOR to ORS	Cargo module undocked from ICV	ICV arrival in ORS vicinity	LOP-G orbit	Electric orbit raising from LOP-G to ORS orbit	Lunar orbit	Loaded
7.	Rendezvous and docking with ORS	ICV arrival in ORS vicinity	Cargo module docked to ORS	ORS orbit	Operations required in ORS vicinity to dock Cargo module to ORS refueling docking port	Lunar orbit	Loaded
8.	Refueling	Cargo module docked to ORS	ICV refuelled	ORS orbit	Operations required to transfer fuel to ICV tank throughout Cargo module	Lunar orbit	Loaded
9.	Undocking from ORS	ICV refuelled	Cargo module undocked from ORS	ORS orbit	Operations required to undock Cargo module from ORS	Lunar orbit	Loaded
10.	ORS – MOS EOR	Cargo module undocked from ORS	ICV arrival in MOS vicinity	ORS orbit	Electric orbit raising required to reach the MOS orbit	Deep space	Loaded
11.	Rendezvous and docking with MOS	ICV arrival in MOS vicinity	Cargo module docked to MOS	MOS orbit	Operations required in MOS vicinity to dock Cargo module with MOS docking port	Mars orbit	Loaded
12.	Checking and Cargo handling at MOS	Cargo module docked to MOS	Cargo module managed	MOS orbit	Operations required to verify the proper functioning of ICV and to deliver/ retrieve cargo assets	Mars orbit	Loaded

Table 5.7: Table of phases **2d** (first part)

13.	Undocking from MOS	Cargo module managed	Cargo module undocked from MOS	MOS orbit	MOS orbit	Operations required to undock Cargo module from MOS	Mars orbit	Loaded
14.	MOS – LOP-G EOR	Cargo module undocked from MOS	ICV arrival in LOP-G vicinity	MOS orbit	LOP-G orbit	Electric orbit raising required to reach the LOP-G orbit	Deep space	Loaded
15.	Rendezvous and docking with LOP-G	ICV arrival in LOP-G vicinity	Cargo module docked to LOP-G	LOP-G orbit	LOP-G orbit	Operations required in LOP-G vicinity to dock Cargo module with LOP-G docking port	Lunar orbit	Loaded
16.	Logistics, checking and maintenance	Cargo module docked to LOP-G	ICV ready for cargo handling procedure	LOP-G orbit	LOP-G orbit	Operations required to verify and guarantee the proper functioning of ICV	Lunar orbit	Loaded
17.	Berthing and undocking	ICV ready for cargo handling procedure	ICV undocked from old Cargo module docking port	LOP-G orbit	LOP-G orbit	Operations required to attach ICV grasping mechanism to LOP-G robotic arm and to undock ICV from old Cargo module	Lunar orbit	Loaded
18.	Relocation to new Cargo module	ICV undocked from old Cargo module docking port	ICV ready for docking to new Cargo module docking port	LOP-G orbit	LOP-G orbit	Mechanical displacement of the ICV, by means of LOP-G robotic arm, from old Cargo module docking port to new Cargo module docking port	Lunar orbit	Not Loaded
19.	Docking and release	ICV ready for docking to new Cargo module docking port	ICV released by LOP-G robotic arm	LOP-G orbit	LOP-G orbit	Operations required to dock ICV at new Cargo module docking port and to detach ICV grasping mechanism from LOP-G robotic arm	Lunar orbit	Not Loaded
D1.	Undocking from Cargo module	Cargo module docked to LOP-G	ICV undocked from Cargo module	LOP-G orbit	LOP-G orbit	Operations required to undock ICV from Cargo module	Lunar orbit	Not loaded
D2.	EOR to graveyard orbit and switch-off	ICV undocked from Cargo module	ICV completely switched off	LOP-G orbit	Graveyard orbit	Electric orbit raising from LOP-G orbit to graveyard orbit and system shutdown	Cis-lunar	Not loaded

Table 5.8: Table of phases **2d** (second part)

5.4.5 Design Reference Mission - 2d

The extended launch phase (represented in Figure 5.8 by the Roman number "I") includes launch, early operations, EOR to LOP-G and rendezvous and docking at LOP-G phases previously described in Section 5.3.3. The only difference specified is the used docking port; in this scenario is required, only for the first contact with the station, to dock directly with the Cargo Module docking port.

At this point, the extended operative phase (represented in Figure 5.8 by the Roman number "II") can begin. Subsequently, undocking from LOP-G, EOR to ORS, rendezvous and docking at ORS, refueling through the Cargo Module and undocking from ORS phases are carried out in sequence. After have accomplished all these operations, the spacecraft, with its cargo module, separates from the station and starts the third electric orbit rising with the aim of reaching the MOS orbit.

All the phases between the EOR to MOS orbit and the EOR returning to LOP-G orbit are the same as the previously described in Section 5.3.3.

Once the lunar station orbit is reached, the rendezvous and docking phase is accomplished at the LOP-G docking port. Subsequently, logistic, checking, maintenance, berthing and undocking, relocation to new Cargo Module and docking and release phases are carried out in sequence. In such a way the mission cycle can proceed until disposal.

The extended disposal phase (represented in Figure 5.9 by the Roman number "III"), which includes undocking from Cargo Module, EOR to graveyard orbit and system switch-off, represents the ICV end-of-life and the irreversible mission conclusion.

In Figure 5.8 and Figure 5.9 is shown the related DRM.

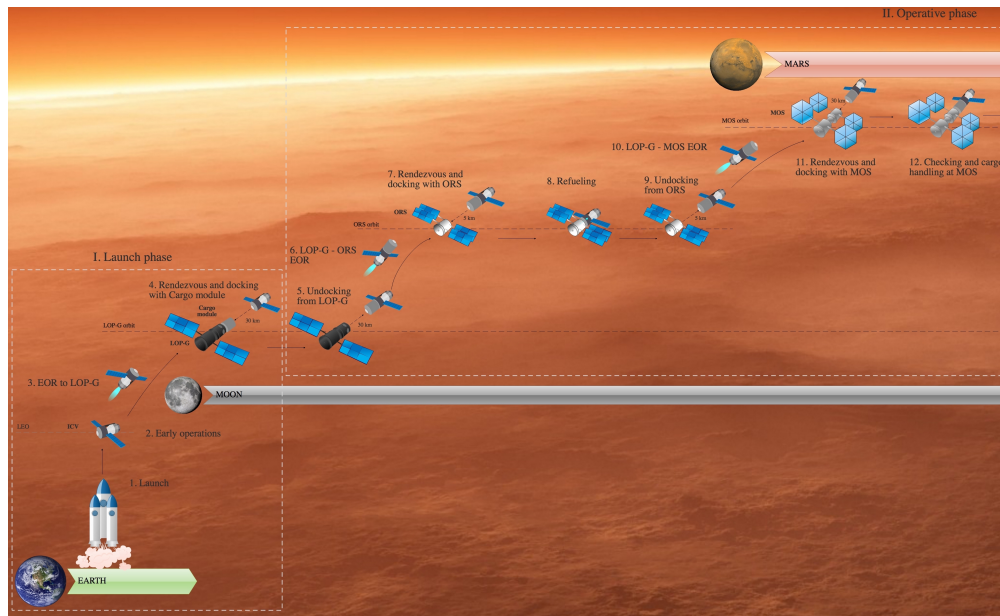


Figure 5.8: Design Reference Mission **2d** (first part)

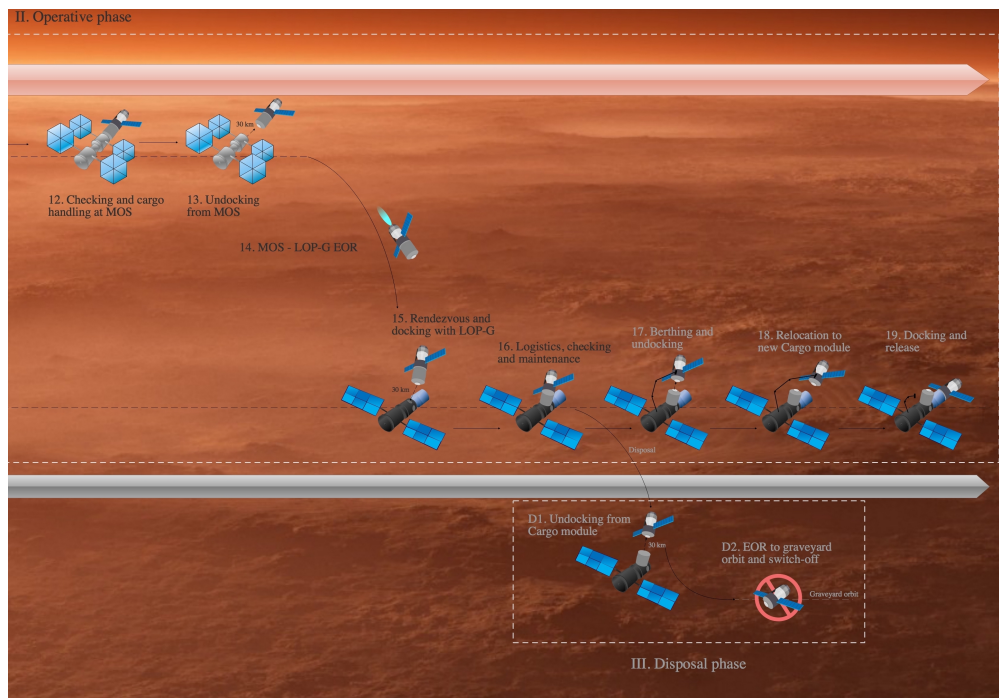


Figure 5.9: Design Reference Mission **2d** (second part)

5.4.6 Phases Block Diagram - 2d

In accordance with the considerations made about the Scenario 2a, the first part of the diagram represents the launch phase, which is constituted by the phases necessary to start the effective operating cycle, that are phases 1,2,3 and 4.

The second part of the diagram represents the operational phase, which is constituted by the phases necessary to perform the effective operating cycle of the transportation mission, it is constituted by phases 5 to 19. These ones are repeated identically until the mission end.

The third part of the diagram represents the disposal phase, which is constituted by the phases necessary to perform the disposal and the end-of-life operations. It is constituted by phases D1 and D2.

As reported in the previous Section 5.3.4, a color coding has been used to facilitate understanding of the blocks. In detail, each color corresponds to a reached orbit: green for Earth orbit/cislunar space, grey for Lunar orbit, light blue for Deep space and Orange for Mars orbit. In addition, a stream of arrows guides the succession of the different phases. In Figure 5.10 is shown the relative PBD.

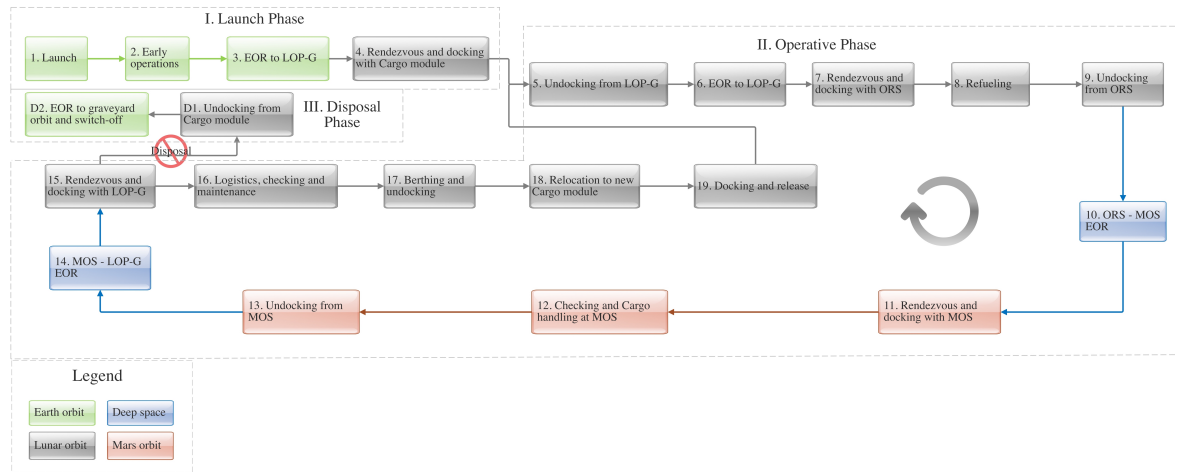


Figure 5.10: Phases Block Diagram 2d

5.5 Modes of Operations

5.5.1 Building Blocks Status

As introduced in the previous Section, several building blocks are involved in the ICV mission phases. In particular, each one can be characterized by a different mode of operation along the whole mission, representing the status of the element in all the ICV mission phases. The status of the system represents the operations that the system itself is capable of performing. Three main status have been identified in order to describe the role of the different segments in each mission phase:

Operational constitutes the active status of the segment, during which it is able to participate actively in the mission phase.

Dormant constitutes the passive status of the segment during which the segment is not able to participate actively in the mission phase and provides only a passive contribution to the performance of the mission.

Safe constitutes the contingency status of the segment, i.e. the safe mode. Active and passive operations are required to restore the system. The segment mission is temporarily suspended.

In accordance with the functional analysis conducted in *Chapter 3*, the constitution of the considered building blocks is:

1. Space segment: ICV, Cargo module;
2. Launch segment: Launch Vehicle, Launch Control Station;
3. Ground segment: Mission Control Center, Mission Logistic Center;
4. Lunar space segment: LOP-G, Lunar Navigation Satellites;
5. Mars space segment: MOS, Mars Navigation Satellites, Mars Communication Satellites.

For each segment we can described and characterized the possible status it can enter. They represent a generic condition of the segment and are indicated as follows:

1. Space segment

- *Operational*: all systems necessary to perform the required operations are active.
- *Dormant*: only systems necessary to monitor the system and to survive the external environment are active.

2. Launch segment

- *Operational*: all systems necessary to perform launch operations are active.

3. Ground segment

- *Operational*: all systems necessary to perform monitor and command operations are active.
- *Dormant*: only systems necessary to monitor the telemetry data are active.

4. Lunar Space segment

- *Operational*: all systems necessary to perform the required operations are active.
- *Dormant*: only systems necessary to monitor rendezvous and docking operations are active.

5. Mars Space segment

- *Operational*: All systems necessary to perform the required operations are active.
- *Dormant*: only systems necessary to monitor rendezvous and docking operations are active.

5.5.2 ICV Modes of Operations

During each mission phase, the ICV can enter various modes of operations. Unlike the mission phases, which are related to the external environment in which the system operates, we define a mode of operation by establishing which components and equipments are active or not active within that specific mode. Therefore, unlike the mission phases which focus on the external environment, the modes of operations focus on the system itself and how it does work. Different modes of

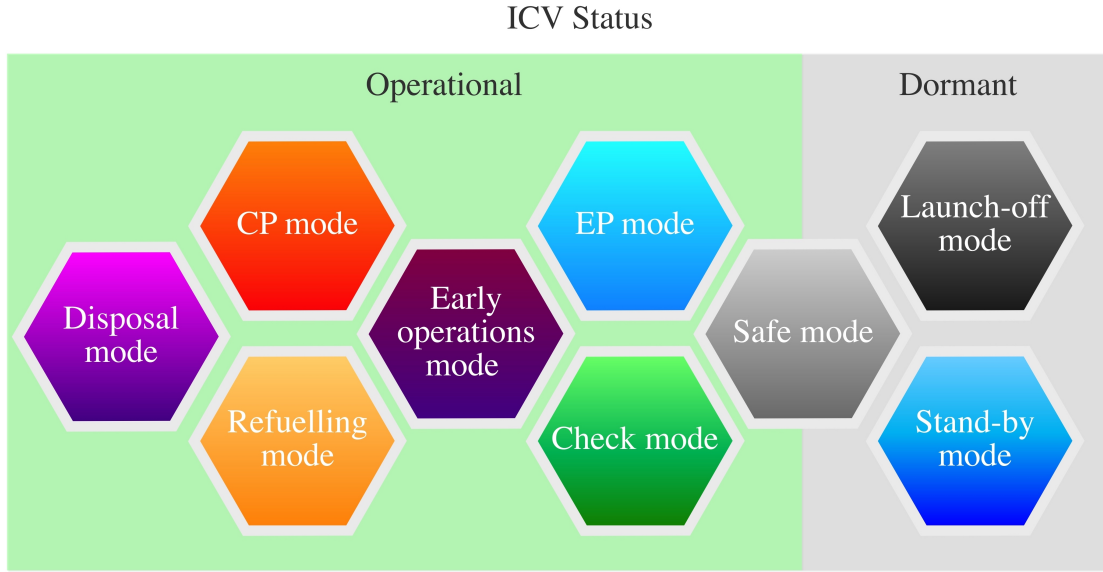


Figure 5.11: Modes of Operations Classification

operation can be envisaged in the same mission phase. The *Figure 5.11* shows all possible modes of operations that can be entered by the ICV during its mission.

ICV components can be activated at different power level in order to ensure the correct execution of the mission phases. Each mode of operation is characterized by a specific components power level configuration. Preliminary, the main power standard identified are:

- F** Full operative, component can be activated up to nominal power level.
- H** High operative, component can be activated up to $2/3$ nominal power level.
- L** Low operative, component can be activated up to $1/3$ nominal power level.
- I** Not operative, components are inactive.

In accordance to the status type (operational, dormant and safe), the modes of operations that allow the proper execution of the mission have been identified. In the case of modes of operations concerning the operational status, the modes of operations have been specified at a lower level, with the aim of ensuring a more detailed characterization of the fundamental features of the ICV.

- Operational status:

1. *Check mode*

ICV components' necessary to check the systems' health status are activated and the data obtained from the analysis are sent to the ground. This operative mode can be activated exclusively when ICV is docked to LOP-G or MOS.

- *Nominal check mode*: ICV components' health status is checked in sequence (excluding the EP and CP subsystems).
- *Check report mode*: system check report is processed and sent to the ground.

2. *Electric propulsion (EP) mode*

The ICV electric propulsion system is briefly checked, prepared to full operative mode and, after receiving the ignition command, main HETs are activated in full operative mode. Simultaneously, all ICV components necessary to perform the orbit transfer are activated. This operative mode can be activated exclusively when ICV is adequately far from the LOP-G/MOS/ORS with the aim to guarantee the stations' safety. The safety distance from manned and unmanned stations is considered relatively in 30 km and in 5 km.

- *EP check mode*: a brief check of the main HETs and the feeding system's health status is performed.
- *Idle mode*: main HETs and the feeding system are prepared to full operative mode and ready for receive the ignition command.
- *EOR mode*: main HETs are activated at full operative mode and all ICV components necessary to perform the orbit transfer are activated.

3. *Chemical propulsion (CP) mode*

The ICV chemical propulsion system is activated to perform the whole rendezvous phase and docking interface is activated to conclude the attachment to the stations. This operative mode can be activated when ICV is adequately close to the LOP-G/MOS/ORS with the aim to ensure adequate attitude and orbit control. The close distance from manned and unmanned stations is considered relatively in 30 km and in 5 km.

- *CP maneuvers mode*: ICV chemical propulsion system is activated to perform close rendezvous, final approach, first and second hovering maneuvers. Moreover, attitude control system and its actuators are in full operative mode.

- *Mating mode*: berthing interface is exploited to perform the attachment between grasping mechanism and LOP-G robotic arm (if present). The operational berthing distance is considered in 2 m. Docking interface is activated to perform the attachment to the LOP-G/MOS/ORS. The operational docking distance is considered in 0 m.

4. *Refueling mode*

The ICV fluid plane is aligned, connections are established and valves are sealed; ICV tanks are filled and fluid plane disconnected. The correct execution of the operations is verified. This operative mode can be activated exclusively when ICV is docked to LOP-G/ORS refueling docking port and docking interface is active.

- *Connection & sealing mode*: ICV fluid plane is aligned with LOP-G/ORS fluid plane, all connections are established and the valves are sealed.
- *Tanks filling mode*: fuel is pumped by the LOP-G/ORS refueling system to the ICV tanks and, at the end of the procedure, all the fluid connections are disconnected.
- *Refueling check mode*: the correct ICV tanks filling and the fluid plane disconnection are verified.

5. *Early operations mode*

ICV components' are activated, orbit is determined and the attitude is acquired for the first time, a test orbit change is performed with the aim to control and calibrate the concerned components. This operative mode can be activated exclusively after separation from launcher, ICV inserted into LEO.

- *Switch-on mode*: ICV components' are activated after Launch-off mode (excluding the EP and CP subsystems).
- *Orbit determination & attitude acquisition mode*: ICV Orbit is determined and the attitude is acquired for the first time with the aim to check the dedicated components.
- *Orbit change mode*: electrical and chemical propulsion systems are activated for the first time with the aim to check the dedicated components.
- *Calibration & control mode*: orbit and attitude are once more acquired with the aim to control the correct functioning of the propulsion systems and to calibrate the attitude and communication systems.

6. *Disposal mode*

ICV components' are activated at low power level to perform the transfer towards the graveyard orbit. The minimum amount of fuel required to perform the transfer is present in the tanks. In graveyard orbit, the final shutdown of the entire system is executed. This operative mode can be activated exclusively when ICV is separated from LOP-G, is located in cislunar orbit and his operational life is ended.

- *Disposal transfer mode*: main HETs are activated at low operative mode. All ICV component's necessary to perform the orbit transfer are activated at the lowest possible power level and with the sole purpose of reaching the graveyard orbit.
- *Switch-off mode*: all ICV component's are switched off and no longer recoverable.

- Dormant status:

7 *Stand-by mode*: ICV component's necessary to monitor the system and to survive the external environment are active with the sole purpose of protecting the spacecraft. In addition, the communication system is activated at low operative mode to allow the commands reception.

8 *Launch-off mode*: ICV is allocated in the launcher. The clamping interface is engaged and OBC is activated at low power level in order to recognize the separation signal. All others components is in not operative mode.

- Safety Status:

9 *Safe mode*

Solar arrays are fully oriented towards sun, all non-essential components are deactivated, a system safety check is performed and telemetry data are sent to the ground. This operative mode can be activated at any time. Power system and AOCS are considered essential components, their non-critical failures are bypassed through redundancies; critical failures of these components cause the loss of the mission. Safe mode involves failures mainly related to thermal control and communication system. The main purpose of this mode is to safely reach LOP-G/ORS in order to perform the necessary maintenance operations.

- *Sun orientation mode*: double side solar arrays orientation is modified in order to get as much sun exposure as possible with the objective of supplying the maximum possible electric power to the spacecraft.

- *Safety check mode*: all non-essential components are deactivated, essential components are activated at low power level and a check of the subsystem affected by the anomaly is performed.
- *Safety report mode*: safety check report is processed and sent to the nearest station.

In Figure 5.12 the Operative Modes of Operations are shown graphically, to each block corresponds a MoO with the related sub-modes. The used colors have the sole purpose of qualitatively representing, as faithfully as possible, the active components.

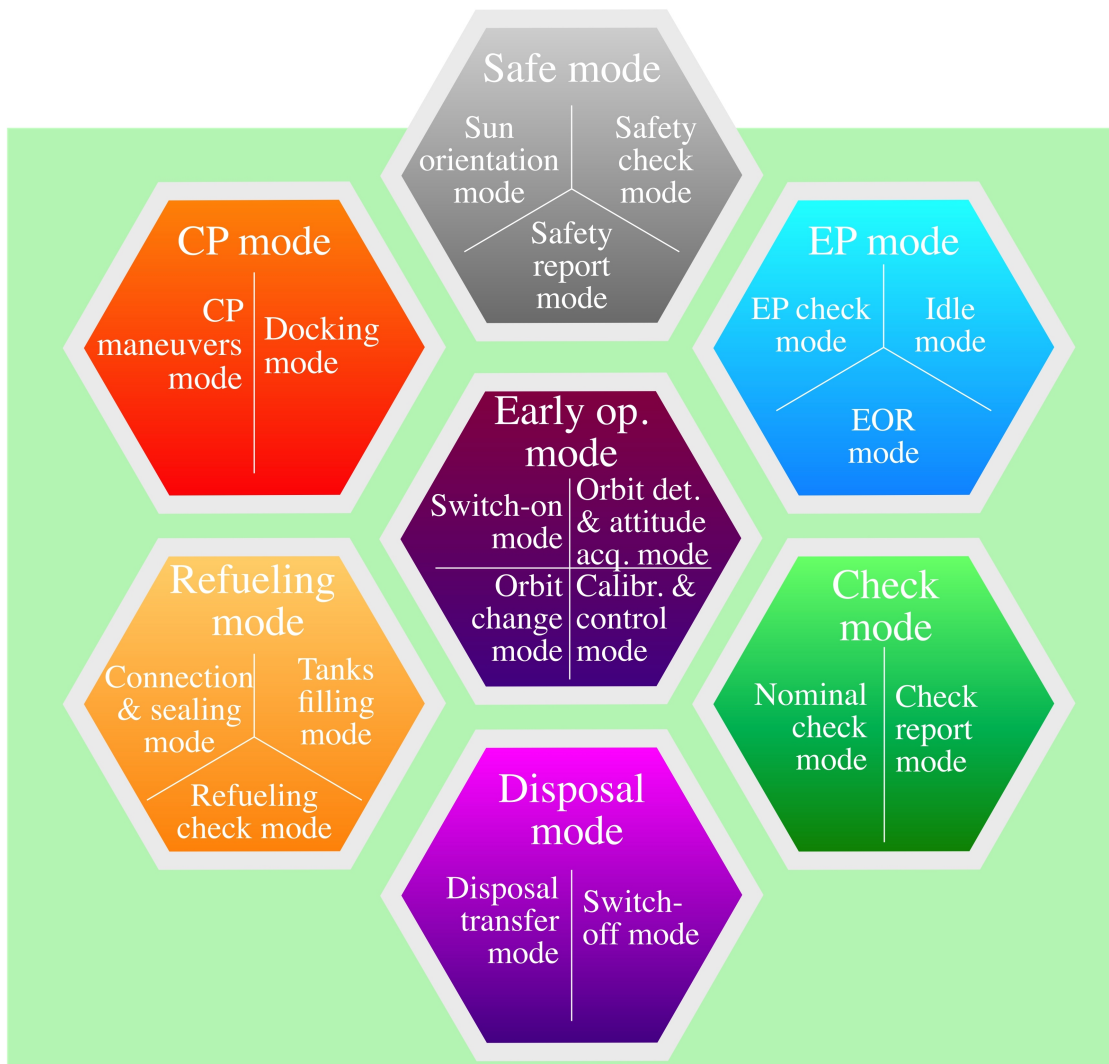


Figure 5.12: ICV Operative Modes of Operations

In the following Table 5.9 and Table 5.10 the MoO have been characterized and the active components have been indicated. Furthermore, for each component, the coding presented in the legend has been used in order to provide an indication of the usable power level of the single component.

Legend:

- F** Component can be activated up to nominal power level (full operative mode)
- H** Component can be activated up to 2/3 nominal power level (high operative mode)
- L** Component can be activated up to 1/3 nominal power level (low operative mode)
- I** Component inactive (not operative)
- A** Component is active (active mode)
“active mode” concerns only interface status.
- O** Component is operative (operative mode)
“operative mode” concerns only solar arrays status and indicates that they are active and able to supply the required power.

Components \ Modes	Stand-by	Launch-off	Check	Safe	EP	CP	Refueling	Disposal
PPU	I	I	I	L	F	I	I	L
Thruster Units	I	I	I	L	F	I	I	L
Feeding system	I	I	I	L	F	I	I	L
Orbit sensors	I	I	H	L	F	F	I	H
Attitude sensors	I	I	H	L	F	F	I	H
AOCS actuators*	I	I	H	L	F	F	I	H
AOCS OBC	I	I	H	L	F	F	I	H
Solar arrays	O	I	O	O	O	O	O	O
Batteries	L	I	H	L	F	F	F	H
PCDU	L	I	H	L	F	F	H	H
Heat pipes	H	I	H	I	F	F	H	H
Radiators	H	I	H	I	F	F	H	H
Electrical heaters	H	I	H	I	F	F	H	H
TCS OBC	H	I	H	I	F	F	H	H
Temperature sensors	H	I	H	I	F	F	H	H
Docking I/F	A	I	A	A	I	A	A	I

Table 5.9: Modes of Operations Characterization (first part)

Fluid Plane	I	I	I	I	I	I	A	I
Fluid couplings	I	I	I	I	I	I	A	I
Electrical connector	I	I	I	I	I	I	A	I
Refueling valves	I	I	I	I	I	I	A	I
Commands decoder	L	I	H	I	F	F	H	H
OBC	L	L	F	L	F	F	H	H
Data Storage Unit	L	I	H	I	F	F	H	H
RIU	L	I	H	I	F	F	H	H
Antennas	L	I	H	I	F	F	H	H
Receiver	L	I	H	I	F	F	H	H
Transmitter	I	I	H	I	F	F	H	H
Auto-tracking equipment	I	I	H	I	F	F	I	H
Data bus	L	I	H	I	F	F	H	H

* In “AOCS actuators” is included also the feeding system.

Table 5.10: Modes of Operations Characterization (second part)

At this point all the possible Modes of Operations in which the ICV can be entered have been described in their main characteristics. The two scenarios previously introduced can be analyzed subsequently in their operational features.

5.5.3 Analysis of Scenario 2a

Building Blocks Status during operations

Remembering the phases described previously in Section 5.4.1, the segment concerned each phase have been identified. In addition, the status of the various segments involved has also been specified, the result are shown in the following Table 5.11. Safety status has not been reported in the table since it is strictly a contingency status. Obviously, each segment can enter this kind of status at any time during any phase.

Phases \ Segments	Space	Launch	Ground	Lunar space	Mars space
1. Launch	D	O	O		
2. Early operations	O		O		
3. EOR to ORS	O		D		
4. Rendezvous and docking with ORS	O		D	D	
5. Refueling	D		D	O	
6. Undocking from ORS	O		D	D	
7. EOR to LOP-G	O		D		
8. Rendezvous and docking with Cargo module	O		D	D	
9. Undocking from LOP-G	O		D	D	
10. LOP-G – MOS EOR	O		D		
11. Rendezvous and docking with MOS	O		D		D
12. Checking and Cargo handling at MOS	D		O		O
13. Undocking from MOS	O		D		D
14. MOS – LOP-G EOR	O		D		
15. Rendezvous and docking with LOP-G	O		D	D	
16. Logistics, checking and maintenance	D		O	O	
17. Undocking from LOP-G	O		D	D	
18. EOR to ORS	O		D		

Table 5.11: Building Blocks Status for Scenario **2a**

ICV MoO during operations

Shifting the attention to the ICV, the Modes of Operations that interest each phase have been analyzed in the following Table 5.12. Analogous to the considerations made beforehand regarding the Safety status, also the "Safe mode" has not been reported in the table since it is strictly a contingency mode and the ICV can enter this kind of mode at any time during any phase.

Phases \ Modes	Launch -off	Early op.	Stand- by	Check	Safe	EP	CP	Ref.	Dispos.
1. Launch	X								
2. Early operations		X							
3. EOR to ORS						X			
4. Rendezvous and docking with ORS							X		
5. Refueling								X	
6. Undocking from ORS							X		
7. EOR to LOP-G						X			
8. Rendezvous and docking with Cargo Module							X		
9. Undocking from LOP-G							X		
10. LOP-G – MOS EOR						X			
11. Rendezvous and docking with MOS							X		
12. Checking and Cargo handling at MOS			X	X					
13. Undocking from MOS							X		
14. MOS – LOP-G EOR						X			
15. Rendezvous and docking with LOP-G							X		
16. Logistics, checking and maintenance				X					
17. Undocking from LOP-G							X		
18. EOR to ORS						X			
D1. EOR to graveyard orbit and switch-off									X

Table 5.12: Modes of Operations for Scenario **2a**

ICV Modes Transition

The transition stable has been developed with the aim of guaranteeing the allowed passage from one mode to another. Furthermore, the transition events have been represented for each mode switch. In following Table 5.13 are shown the information mentioned above:

Modes			Transition event(s)
No.	From	to	
1.	Launch-off	Early operations	ICV is inserted into LEO
2.	Early operations	EP	Early operations are successfully completed
3.	EP	CP	- ICV reach the LOP-G proximity - ICV reach the MOS proximity - ICV reach the ORS proximity
4.	CP	EP	- ICV reach the safety distance from LOP-G - ICV reach the safety distance from MOS - ICV reach the safety distance from ORS
5.	CP	Stand-by	ICV is docked to MOS
6.	CP	Check	ICV is docked to LOP-G (through Cargo module)
7.	Stand-by	Check	End of Cargo module handling at MOS
8.	Check	CP	- ICV is docked to LOP-G (through Cargo module), checked and ready for departure - ICV is docked to MOS, checked and ready for departure
9.	Refueling	CP	ICV fuel tanks are filled
10.	CP	Refueling	ICV is docked to ORS refueling docking port
11.	CP	Disposal	- ICV reach the safety distance from LOP-G - ICV end of life
12.	All	Safe	Anomaly/failure is detected
13.	Safe	All	Anomaly/failure is neutralized or secured

Table 5.13: Modes Transition Table **2a**

The sole transitions between Modes of Operations are those shown in the Table 5.13, every other transition is not allowed for security reasons or mission constrains.

The Modes Transition Diagram shows graphically the transition ways between the different Modes of Operations. The numbers are referred at the previous Table 5.13. The main feature of this diagram is the pivotal representation of the "Safe mode". It is strictly a contingency mode and the ICV can enter this kind of mode at any time from any other MoO, with the exception of "Launch-off mode" (ICV is located into the launcher) and "Disposal mode" (ICV end-of-life is reached).

Phases \ Segments	Space	Launch	Ground	Lunar space	Mars space
1. Launch	D	O	O		
2. Early operations	O		O		
3. EOR to LOP-G	O		D		
4. Rendezvous and docking with Cargo module	O		D	D	
5. Undocking from LOP-G	O		D	D	
6. EOR to ORS	O		D		
7. Rendezvous and docking with ORS	O		D	D	
8. Refueling	D		D	O	
9. Undocking from ORS	O		D	D	
10. ORS – MOS EOR	O		D		
11. Rendezvous and docking with MOS	O		D		D
12. Checking and Cargo handling at MOS	D		O		O
13. Undocking from MOS	O		D		D
14. MOS – LOP-G EOR	O		D		
15. Rendezvous and docking with LOP-G	O		D	D	
16. Logistics, checking and maintenance	D		O	O	
17. Berthing and undocking	D		D	O	
18. Relocation to new Cargo module	D		D	O	
19. Docking and release	D		D	O	

Table 5.14: Building Blocks Status for Scenario **2d**

ICV MoO during operations

Shifting the attention to the ICV, the Modes of Operations that interest each phase have been analyzed in the following Table 5.15. Analogous to the considerations made beforehand regarding the "Safety status" and the Scenario 2a, also the "Safe mode" has not been reported in the table since it is strictly a contingency mode and the ICV can enter this kind of mode at any time during any phase.

Phases \ Modes	Launch -off	Early op.	Stand- by	Check	EP	CP	Ref.	Disposal
1. Launch	X							
2. Early operations		X						
3. EOR to LOP-G					X			
4. Rendezvous and docking with Cargo module						X		
5. Undocking from LOP-G						X		
6. EOR to ORS					X			
7. Rendezvous and docking with ORS						X		
8. Refueling							X	
9. Undocking from ORS						X		
10. ORS – MOS EOR					X			
11. Rendezvous and docking with MOS						X		
12. Checking and Cargo handling at MOS			X	X				
13. Undocking from MOS						X		
14. MOS – LOP-G EOR					X			
15. Rendezvous and docking with LOP-G						X		
16. Logistics, checking and maintenance				X				
17. Berthing and undocking			X					
18. Relocation to new Cargo module			X					
19. Docking and release			X					
D1. Undocking from Cargo module						X		
D2. EOR to graveyard orbit and switch-off								X

Table 5.15: Modes of Operations for Scenario **2d**

ICV Modes Transition

As explained above, the transition stable has been developed with the aim of guaranteeing the allowed passage from one mode to another. Furthermore, the

transition events have been represented for each mode switch. In following Table 5.16 are shown the information mentioned above:

Modes			Transition event(s)
No.	From	to	
1.	Launch-off	Early operations	ICV is inserted into LEO
2.	Early operations	EP	Early operations are successfully completed
3.	EP	CP	- ICV reach the LOP-G proximity - ICV reach the MOS proximity - ICV reach the ORS proximity
4.	CP	EP	- ICV reach the safety distance from LOP-G - ICV reach the safety distance from MOS - ICV reach the safety distance from ORS
5.	CP	Stand-by	ICV is docked to MOS
6.	CP	Check	ICV is docked to LOP-G (through Cargo module)
7.	Check	Stand-by	ICV is docked to LOP-G (through Cargo module) and ready for relocation
8.	Stand-by	Check	End of Cargo module handling at MOS
9.	Check	CP	ICV is docked to MOS, checked and ready for departure
10.	Refueling	CP	ICV fuel tanks are filled
11.	CP	Refueling	ICV is docked (through Cargo module), to ORS refueling docking port
12.	CP	Disposal	- ICV reach the safety distance from LOP-G - ICV end of life
13.	All	Safe	Anomaly/failure is detected
14.	Safe	All	Anomaly/failure is neutralized or secured

Table 5.16: Modes Transition Table **2d**

As the previous considerations for Scenario 2a, the sole transitions between Modes of Operations are those shown in the Table 5.16, every other transition is not allowed for security reasons or mission constrains.

The Modes Transition Diagram shows graphically the transition ways between the different Modes of Operations. The numbers are referred at the previous Table 5.16. The main feature of this diagram is the pivotal representation of the "Safe mode". It is strictly a contingency mode and the ICV can enter this kind of mode at any time from any other MoO, with the exception of "Launch-off mode" (ICV

is located into the launcher) and "Disposal mode" (ICV end-of-life is reached).

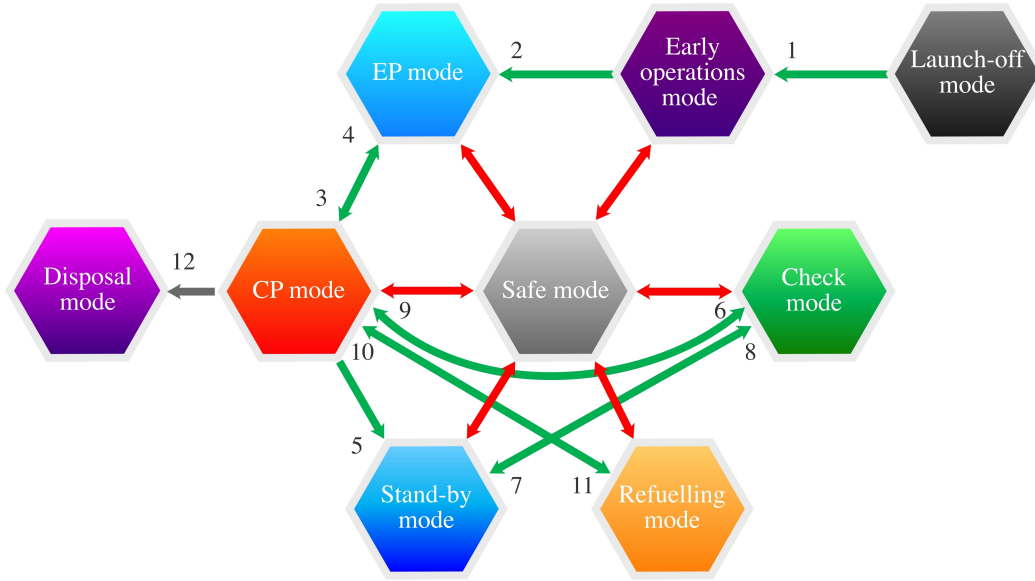


Figure 5.14: Modes Transition Diagram 2d

5.5.5 Operational Requirements

Additional requirements arise from the analysis of the Modes of Operations. They are the *Operational Requirements* and contains recommendations related to the system operability. They express which modes of operation the system shall be able to enter during a specific phase. They also establish the equipment that is active or not in a specific mode and its power level range. For examples:

- The ICV shall be able to enter in Check mode in the "Checking and Cargo handling at MOS" phase;
- In Check mode the Thruster Units shall be inactive;
- In Check mode Orbit Sensors shall be active at a power range between 1/3 and 2/3 of the nominal power level;
- The ICV shall be able to enter in EP mode in the "EOR to LOP-G" phase;
- In EP mode the PPU shall be active at a power range between the nominal power level and 2/3 of the nominal power level;
- In EP mode Docking I/F shall be inactive.

Chapter 6

Trade-off Analysis

A cost-effective and safe system must provide a particular kind of balance between effectiveness and cost: the system must provide the most effectiveness for the resources expended, or equivalently, it must be the least expensive for the effectiveness it provides. This condition is a weak one because there are usually many designs that meet the condition. Design trade studies, an important part of the systems engineering process, often attempt to find designs that provide a better combination of the various dimensions of cost and effectiveness. Trade-off analysis is a method to accomplish design trade studies. Trade-off analysis can be applied at different level of the system design process[12, 13].

6.1 Figures of Merits (FoM)

Figures of Merits are a numerical value representing a measure of effectiveness, efficiency, performance or other important factor, and ascertained or approximated from analysis, appraisal, or estimation techniques.

The Figures of Merits are the fundamental basis of the trade-off analysis and they must be chosen with considerable accuracy. Scenario 2a and Scenario 2d (Section ?? and Section 5.4.4) shows different features. Different refueling operations suggest the necessity to evaluate these differences through a dedicated index. In relation of this, the possible necessity to implement new functions (e.g. LOP-G refueling capability) has been introduced through a dedicated index. In addition, the two scenarios present different cargo capability. Mass, power and cost, being directly proportional to each other in a first approximation, have been taken into account in a single index called "mass". Finally, since the LOP-G and the MOS are manned stations, an index has been introduced that measures the crew safety in relation to the operations performed by the ICV. Therefore, the following Figures

of Merits have been chosen:

- The **mass** index is proportional to the spacecraft cost and power, it is also related to the type of mission, system complexity and maturity level of the utilized technology. Mass index is numerically equal to the mass.
- The **refueling complexity** is related to the system complexity of refueling operations and maturity level of the utilized technology for refueling. Using little-known technologies such as refueling through Cargo Module increase the refueling complexity, whereas a direct refueling interface between the ICV and the servicing system decrease the index. Refueling complexity index is equal to 0 in case of direct refueling interface and equal to 1 in case of refueling through Cargo Module.
- The **new functions exploitation** index is an important FoM. Need for functions not yet foreseen in current concepts such as refueling operations at LOP-G increases the index. New functions exploitation index is directly proportional to the number of new functions introduced.
- The **crew safety** index decreases when refueling operations occur while the crew is on board the refueling infrastructure and increase when refueling is performed at a dedicated unmanned system. Crew safety is equal to 0 in case of refueling operations occur at the LOP-G when crew is on board the station and equal to 1 in case of refueling operations occur an unmanned station.
- The **maximum cargo capacity** index is related to number of tons the system can transfer in compliance with following constrains:
 - maximum number of thrusters in the propulsion configuration shall not exceed 35 units;
 - maximum end-to-end transfer time shall not exceed 3 years.

6.1.1 Weight Factor Estimation

In order to estimate a weight factor per each FoM (i.e. establish how much each FoM is relevant in comparison with all others), it may be useful to compare two FoM at a time instead of one FoM with all others at the same time. This simple task can be accomplished through a matrix. The boxes that present the value 1 indicate that the FoM on the row is more relevant than than the FoM on the column. On the opposite, the boxes that present the value 0 indicate that the

FoM on the row is less relevant than than the FoM on the column. Obviously, the obtained matrix is symmetrical. Weight Factor does not need to be normalized to 10 because, having 5 Figures of Merits, the total sum of the single weights is exactly equal to 10. The Weight Factors have been estimated through the following Table 6.1.

FoM	Mass	Refueling complexity	New functions exploitation	Crew Safety	Maximum Cargo Capacity	Rank/Weight Factor
Mass		1	1	0	1	3
Refueling complexity	0		0	0	1	1
New functions exploitation	0	1		0	0	1
Crew Safety	1	1	1		1	4
Maximum Cargo Capacity	0	0	1	0		1
Total weight factor						10

Table 6.1: Weight Factor Estimation

From the previous table results:

- To maximize "Crew Safety" index is always a priority compared to all others FoM;
- Reducing "Mass" index is a priority compared to "Refueling Complexity" index and "New Functions Exploitation" index but it is minor compared to "Crew Safety" index and "Maximum Cargo Capacity" index;
- Reducing "Refueling Complexity" index is a priority compared to "Maximum Cargo Capacity" index but it is minor compared to "Mass" index, "New Functions Exploitation" and "Crew Safety" index;

- Reducing "New Functions Exploitation" is a priority compared to "Refueling Complexity" index but it is minor compared to "Mass" index, "Crew Safety" index and "Maximum Cargo Capacity";
- Increasing "Maximum Cargo Capacity" index is a priority compared to "New Functions Exploitation" index but it is minor compared to "Mass" index, "Refueling Complexity" index and "Crew Safety" index.

In accordance with the considerations made above, the index with higher weight factor (4) is the "Safety Crew". Sequentially the others four index: "Mass" (3), "Refueling Complexity" (1), "New Functions Exploitation" (1) and "Maximum Cargo Capacity" (1).

6.2 Mission Budgets

In this section, the design process followed to preliminary size the different platforms is briefly described and then the main results are presented. The focal point of the design analysis is twofold. On one side, the ICV is mission-driven, in order to be compliant with the mission needs and constraints, that are: maximum mission duration scheduled in 3 years (1095 days) and maximum number of thrusters set in 35 units. On the other hand, the results analysis is technology-driven: the goal is to optimize the design of all the two platforms to address the ICV development activities, identifying a common optimal working point of the HETs. For each mission scenario, the design results presented in the follows have been obtained exploiting a multi-input (concerned orbits and payload mass configurations) multi-output tool, i.e. the Mission and Space Systems (MISS) design tool [16].

Scenario 2a	
Working point	12
Isp	3100 s
Thrusters tot.	33
Active thrusters	10
Δt	1060.9 days
Δv	11.1516 m/s
Tot. wet mass	$7.3008 \cdot 10^4$ kg
Fuel mass	$2.5503 \cdot 10^4$ kg
Power	200 kW

Table 6.2: Mission Budgets for Scenario **2a**

Scenario 2d	
Working point	12
Isp	3100 s
Thrusters tot.	22
Active thrusters	10
Δt	777.9595 days
Δv	9.4676 m/s
Tot. wet mass	$6.3058 \cdot 10^4$ kg
Fuel mass	$1.9350 \cdot 10^4$ kg
Power	200 kW

Table 6.3: Mission Budgets for Scenario **2d**

The analysis have been carried out for four payload mass configurations: 5000 kg, 10000 kg, 15000 kg and 20000 kg. Concerning the scenario 2d, only the 5000 kg configuration (yellow points series) and the 10000 kg configuration (red points series) have been compliant with the constraints introduced above. Instead, the Scenario 2a is compliant only with the 5000 kg payload mass configuration. For this reason, the following trade-off analysis will be carried out exclusively for 5000 kg payload mass configuration.

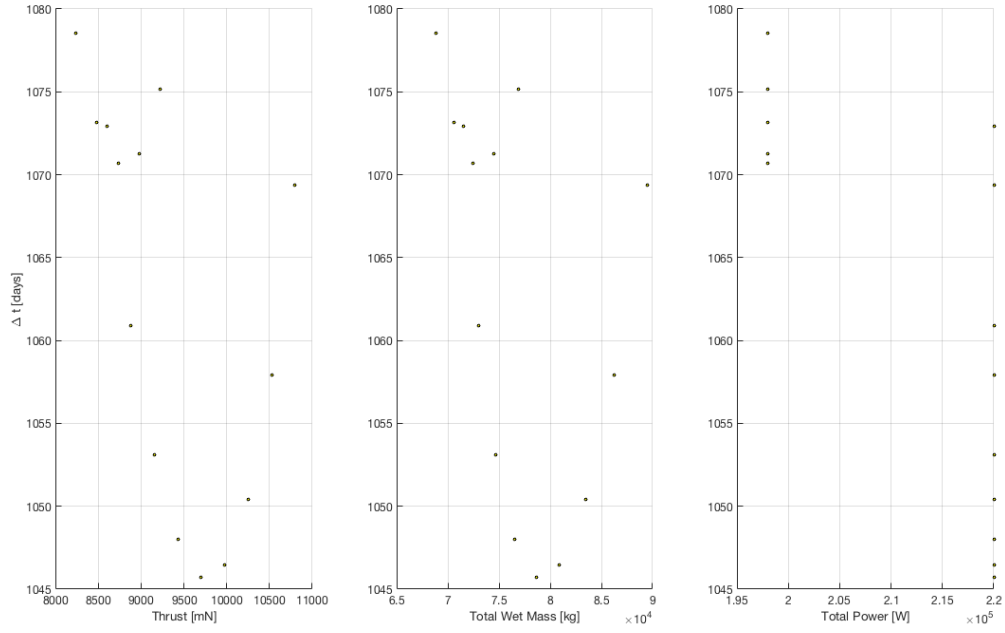


Figure 6.1: Δv - Thrust/Tot. wet mass/Power Diagram **2a**

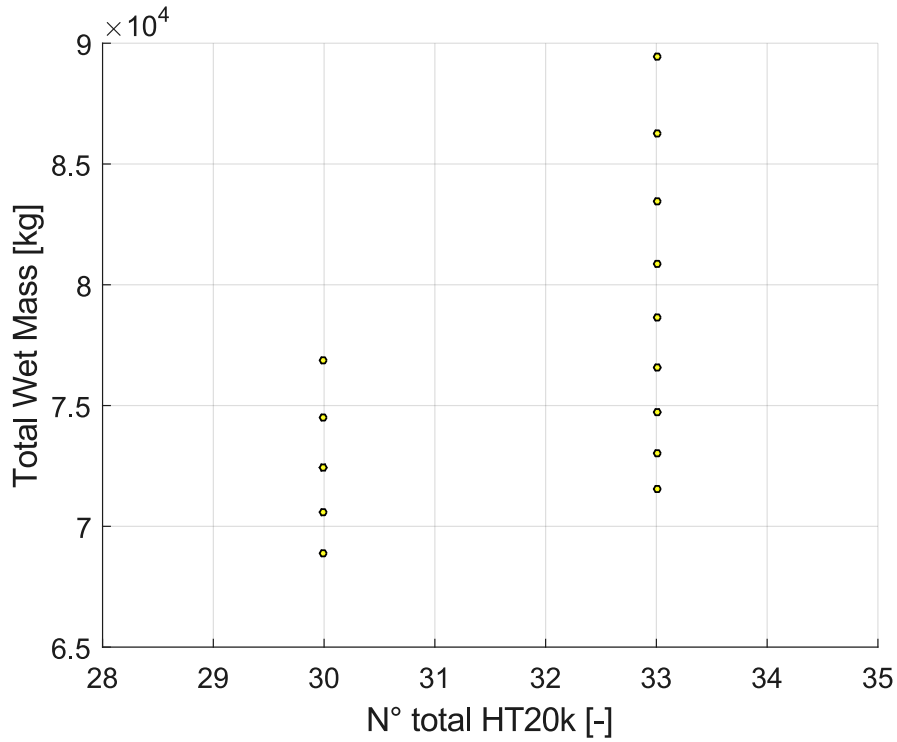


Figure 6.2: Tot. wet mass - N°total HT20K Diagram **2a**

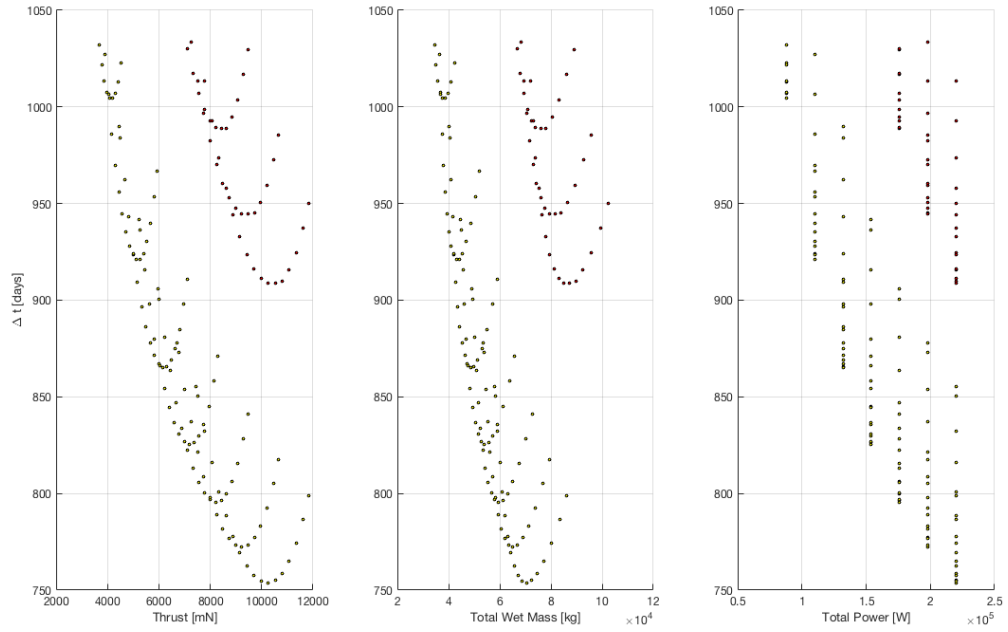


Figure 6.3: Δv - Thrust/Tot. wet mass/Power Diagram **2d**

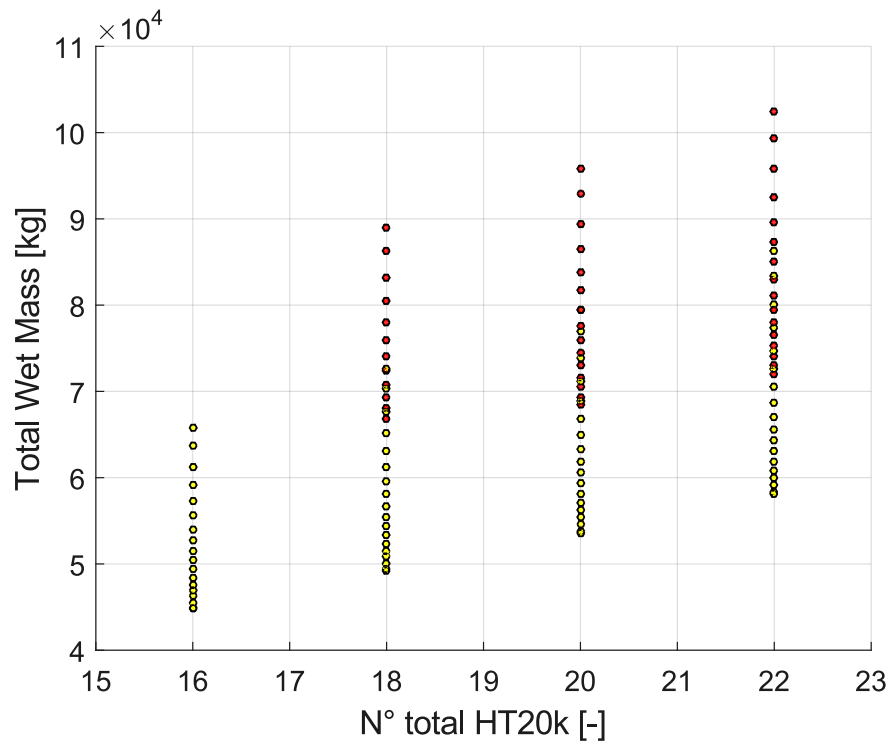


Figure 6.4: Tot. wet mass - N°total HT20K Diagram **2d**

6.3 Trade-off Results

The value index (V) is calculated using eq. (6.1) (first equation, see below) with the normalized parameters (P_i) obtained through eq. (6.2) and (6.3) (respectively second and third equation, see below), where p_i is score index referred to the i -th option. Equation (6.2) is applied to “Crew Safety” and “Maximum Cargo Capacity” because they are proportional to scenario reliability and effectiveness. Equation (6.3) is applied to “Mass”, “Refueling complexity” and “New functions exploitation” that are inversely proportional to scenario reliability and effectiveness.

$$V = \frac{\sum P_i \cdot w_i}{\sum w_i} \quad (6.1)$$

$$P_i = \frac{p_i}{\max(p)} \cdot 10 \quad (6.2)$$

$$P_i = 10 - \frac{p_i}{\max(p)} \cdot 10 \quad (6.3)$$

It should be noted that the assigned scores are values, which are all different for the various FoM considered in the evaluation. It is mandatory that scores are expressed as percentages.

6.3.1 Results for Scenario 2a

In the following Table 6.4 the FoM presented in Section 6.1 have been evaluated according to the described judgment criteria.

FoM	Weight (w _i)	Index Score (p _i)	Comments
Mass	3	$7.3008 * 10^4$	Dry mass [kg] of the ICV excluding the Cargo Module
Refueling complexity	1	1	Refueling occur through the Cargo Module
New functions exploitation	1	1	1 new function assigned to the LOP-G: ICV relocation through robotic arm
Crew Safety	4	1	Refueling operations occur at the ORS (unmanned station)
Maximum Cargo Capacity	1	5000	Cargo carrying capabilities is up to 5000 kg

Table 6.4: Scores of the different Figures of Merits **2a**

The following Table 6.5 has been obtained by applying the proper equation among eq.(6.2) and eq.(6.3), and eq.(6.3) to the index score p_i obtained above.

FoM	Weight (w _i)	Normalized parameter (P _i)	Result (V)
Mass	3	0	0
Refueling complexity	1	0	0
New functions exploitation	1	5	5
Crew Safety	4	10	40
Maximum Cargo Capacity	1	5	5
			50/10 = 5

Table 6.5: Results for Scenario **2a**

6.3.2 Results for Scenario 2d

In the following Table 6.6 the FoM presented in Section 6.1 have been evaluated according to the described judgment criteria.

FoM	Weight (w_i)	Index Score (p_i)	Comments
Mass	3	$6.3058 * 10^4$	Dry mass [kg] of the ICV excluding the Cargo Module
Refueling complexity	1	0	Refueling occur through direct interface between the ICV and the LOP-G
New functions exploitation	1	0	0 new function assigned to the LOP-G are present
Crew Safety	4	1	Refueling operations occur at the ORS (unmanned station)
Maximum Cargo Capacity	1	5000	Cargo carrying capabilities is up to 5000 kg

Table 6.6: Scores of the different Figures of Merits **2d**

The following Table 6.7 has been obtained by applying the proper equation among eq.(6.2) and eq.(6.3), and eq.(6.3) to the index score p_i obtained above.

FoM	Weight (w_i)	Normalized parameter (P_i)	Result (V)
Mass	3	1.36	4.08
Refueling complexity	1	10	10
New functions exploitation	1	10	10
Crew Safety	4	10	40
Maximum Cargo Capacity	1	5	5
			$69.08/10 \cong \mathbf{6.91}$

Table 6.7: Results for Scenario **2d**

6.3.3 Trade-off Conclusion

The value index (V) was calculated for all mission scenario options previously presented in Chapter 5. Results are reported in the table below. The highest value was achieved by scenario **2d**.

Scenario	Value index (V)
2d	6.91
2a	5

Table 6.8: Trade-off Conclusion table

As shown in Table 6.8, scenarios 2d provide solution more reliable and efficient rather than scenarios 2a.

Conclusion

The presented study has carried out the analysis of cargo transfer scenario of an high-power electric spacecraft. The analysis proposed involves both the functional and operational aspects of the mission by means of two main iterative and recursive processes: the Functional Analysis and the Concept of Operations. It also gives evidence of how different categories of requirements can be derived from the main tools used during the analysis. Eventually, a trade-off analysis has been conducted to determine, through the evaluation of appropriate figure of merits, which scenario could be the best one, in terms of cost-effectiveness. Future activities should improve the analysis of this study, extending it to the following areas:

- the complete design and sizing of the spacecraft's subsystems;
- the mission trajectory design;
- the development of additional documents of the Concept of Operations: End-to-end Communication Strategy, Command and Data Architecture, Operational Facilities, Integrated Logistic Support and Critical Events;
- the evaluation of the Risk Assessment.

The examination of these areas would allow a thorough definition of the mission. It would provide details of different aspects that lead a mission to fulfill its initial objectives.

Appendix A

Traceability of Requirements

Each requirement provided in this section is identified through a Requirement ID (Req ID), a unique denomination which contains information about the followings:

- the category to which it belongs, provided through the initials. For example "fr" stands for "functional requirement".
- the requirement from which it derives, within the same category.

When some requirements derive from an other one, within the same category, the Req IDs gives evidence of this relation in the following way: The IDs of the low-level requirements contain number from "1" to "9" in the same position where the ID of the top-level requirement had a "0". For sake of clarity, the functional requirement *fr_1-000-000-000* generates the requirements identified as *fr_1-100-000-000* and *fr_1-200-000-000*. Analogously, these requirements generates the requirements identified as *fr_1-110-000-000* and *fr_1-210-000-000*.

When the requirements deriving from a previous one are more than 9, the list continues as "...9-1", "...9-2" and so on.

For some categories, when the top-level requirements are more than 9, such as for the interface and the operational ones, a letter of the alphabet is indicated in the ID. Starting from "A", a sequence of 9 requirements with the same letter is shown followed by a sequence with the following letters in the alphabetic order.

A.1 Mission and Programmatic Requirements

REQ ID	DESCRIPTION	DEPENS ON	AFFECTS
Mission Requirements			
mr_10	The mission shall support the cis-Martian space exploration		fr_1-000-000; fr_2-000-000; fr_3-000-000; fr_4-000-000
mr_20	The mission shall provide transportation system between LOP-G and MOS		fr_1-000-000; fr_2-000-000; fr_3-000-000; fr_4-000-000; pr_10
mr_30	The mission shall sustain MOS development, evolution, operations and crew support		pr_20; pr_40
mr_40	The transportation system shall exploit electric propulsion		fr_2-111-111
mr_50	The transportation system shall transfer end-to-end unmanned payloads		fr_1-000-000; fr_2-000-000; fr_3-000-000; fr_4-000-000; pr_50
mr_60	ICV shall be a reusable system		mr_61
mr_61	ICV shall be able to perform on-orbit refueling	mr_60	pr_30; fr_3-200-000
Programmatic Requirements			
pr_10	ICV shall exploit existing infrastructures	mr_20	pr_11
pr_20	ICV shall support Mars Mission during all phases in mission timeframe	mr_30	
pr_30	Existing space facilities for on-orbit refueling shall be exploited	mr_61	
pr_40	Cargo shall be delivered within TBD months	mr_30	
pr_11	Mating elements and rendezvous and docking interfaces shall be standardized	pr_10	
pr_50	Unmanned operations autonomy shall be enhanced	mr_50	

Table A.1: Mission and Programmatic Requirements

A.2 System of Systems Requirements

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Functional Requirements			
fr_1-000-000	Launch capabilities shall be provided	mr_10; mr_50; mr_50	fr_1-100-000; fr_1-200-000
fr_2-000-000	Transportation shall be performed	mr_10; mr_20; mr_50	fr_2-100-000; fr_2-200-000
fr_3-000-000	Mission support from orbit shall be provided	mr_10; mr_20; mr_50	fr_3-100-000; fr_3-200-000; fr_3-300-000; fr_3-400-000; fr_3-500-000; fr_3-600-000; fr_3-700-000; fr_3-800-000
fr_4-000-000	Mission support from Earth shall be provided	mr_10; mr_20; mr_50	fr_4-100-000; fr_4-200-000
fr_1-100-000	Orbit insertion shall be performed	fr_1-000-000	fr_1-110-000
fr_1-200-000	Launch support capabilities shall be provided	fr_1-000-000	fr_1-210-000
fr_2-100-000	Unmanned cargo transfer between cislunar and mars environment shall be accomplished	fr_2-000-000	fr_2-110-000
fr_2-200-000	Cargo containing capabilities shall be furnished	fr_2-000-000	fr_2-210-000
fr_3-100-000	Fuel storage capabilities shall be provided	fr_3-000-000	fr_3-110-000
fr_3-200-000	On-orbit refuelling capabilities shall be provided	fr_3-000-000; mr_61	fr_3-210-000
fr_3-300-000	Communication capabilities with ground shall be provided	fr_3-000-000	fr_3-310-000
fr_3-400-000	Navigation capabilities from lunar orbits shall be provided	fr_3-000-000	fr_3-410-000
fr_3-500-000	Communication capabilities from mars orbits shall be provided	fr_3-000-000	fr_3-510-000
fr_3-600-000	Navigation capabilities from mars orbits shall be provided	fr_3-000-000	fr_3-610-000
fr_3-700-000	Habitat capabilities in cislunar orbit shall be provided	fr_3-000-000	fr_3-710-000
fr_3-800-000	Habitat capabilities in mars orbit shall be provided	fr_3-000-000	fr_3-810-000
fr_4-100-000	Mission control capabilities shall be ensured	fr_4-000-000	fr_4-110-000
fr_4-200-000	Mission logistic capabilities shall be ensured	fr_4-000-000	fr_4-210-000

Table A.2: Functional Requirements - System of Systems

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Functional Requirements - Refinement			
fr_1-110-000	Launch Vehicle shall provide ICV orbit insertion capabilities	fr_1-100-000	
fr_1-210-000	Launch Control Station shall provide launch support capabilities	fr_1-200-000	
fr_2-110-000	ICV shall accomplish unmanned cargo transfer between cislunar and mars environment	fr_2-100-000	fr_2-111-000; fr_2-112-000; fr_2-113-000; fr_2-114-000; fr_2-115-000; fr_2-116-000; fr_2-117-000; fr_2-118-000; fr_2-119-1-000; fr_2-119-2-000; fr_2-119-3-000; fr_2-119-4-000; fr_2-119-5-000
fr_2-210-000	Cargo Module shall furnish containing cargo capabilities	fr_2-200-000	
fr_3-110-000	ORS shall provide fuel storage capabilities	fr_3-100-000	
fr_3-210-000	ICV shall provide on-orbit refuelling capabilities	fr_3-200-000	fr_3-211-000; fr_3-212-000
fr_3-310-000	ICV shall provide communication capabilities with ground	fr_3-300-000	fr_3-311-000; fr_3-312-000
fr_3-410-000	Lunar Navigation Satellites shall provide navigation capabilities from lunar orbits	fr_3-400-000	
fr_3-510-000	Mars Communication Satellites shall provide communication capabilities from mars orbits	fr_3-500-000	
fr_3-610-000	Mars Navigation Satellites shall provide navigation capabilities from mars orbits	fr_3-600-000	
fr_3-710-000	LOP-G shall provide habitat capabilities in cislunar orbit	fr_3-700-000	
fr_3-810-000	MOS shall provide habitat capabilities in mars orbit	fr_3-800-000	
fr_4-110-000	Mission Control Center shall ensure mission control capabilities	fr_4-100-000	
fr_4-210-000	Mission Logistic Center shall ensure mission logistic capabilities	fr_4-200-000	
Configuration Requirements			
cr_1	The Launch Segment shall consist of the Launch Vehicle and the Launch Control Station		
cr_2	The Space Segment shall consist of the ICV, the Cargo Module, the LOP-G, the ORS, the MOS, the Lunar Navigation Satellites, the Mars Communication Satellites and the Mars Navigation Satellites		
cr_3	The Ground Segment shall consist of the Mission Control Center and the Mission Logistic Center		

Table A.3: Functional Requirements Refinement and Configuration Requirements
- System of Systems

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Interface Requirements			
ir_A_10	ICV shall interface with Launch Vehicle		ir_A_11; ir_A_12
ir_A_20	ICV shall interface with Cargo Module		ir_A_21; ir_A_22; ir_A_23
ir_A_30	ICV shall interface with Lunar Navigation Satellites		ir_A_31; ir_A_32
ir_A_40	ICV shall interface with LOP-G		ir_A_41; ir_A_42; ir_A_43
ir_A_50	ICV shall interface with ORS		ir_A_51; ir_A_52; ir_A_53; ir_A_54
ir_A_60	ICV shall interface with MOS		ir_A_61; ir_A_62; ir_A_63
ir_A_70	ICV shall interface with Mars Communication Satellites		ir_A_71; ir_A_72
ir_A_80	ICV shall interface with Mars Navigation Satellites		ir_A_81; ir_A_82
ir_A_90	ICV shall interface with Mission Control Center		ir_A_91; ir_A_92
ir_B_10	ICV shall interface with Mission Logistic Center		ir_B_11; ir_B_12
ir_B_20	Launch Vehicle shall interface with ICV		ir_B_21; ir_B_22
ir_B_30	Launch Vehicle shall interface with Launch Control Station		ir_B_31; ir_B_32
ir_B_40	Launch Control Station shall interface with Launch Vehicle		ir_B_41; ir_B_42
ir_B_50	Cargo Module shall interface with ICV		ir_B_51; ir_B_52; ir_B_53
ir_B_60	Cargo Module shall interface with LOP-G		ir_B_61
ir_B_70	Cargo Module shall interface with MOS		ir_B_71
ir_B_80	LOP-G shall interface with ICV		ir_B_81; ir_B_82; ir_B_83
ir_B_90	LOP-G shall interface with Cargo Module		ir_B_91
ir_C_10	Lunar Navigation Satellites shall interface with ICV		ir_C_11; ir_C_12
ir_C_20	Mars Navigation Satellites shall interface with ICV		ir_C_21; ir_C_22
ir_C_30	MOS shall interface with ICV		ir_C_31; ir_C_32; ir_C_33
ir_C_40	MOS shall interface with Cargo Module		ir_C_41
ir_C_50	MOS shall interface with Mars Communication Satellites		ir_C_51; ir_C_52
ir_C_60	Mars Communication Satellites shall interface with ICV		ir_C_61; ir_C_62
ir_C_70	Mars Communication Satellites shall interface with MOS		ir_C_71; ir_C_72
ir_C_80	Mars Communication Satellites shall interface with Mission Control Center		ir_C_81; ir_C_82
ir_C_90	Mission Control Center shall interface with ICV		ir_C_90; ir_C_91

Table A.4: Interface Requirements (part1) - System of Systems

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Interface Requirements			
ir_D_10	Mission Control Center shall interface with Mars Communication Satellites		ir_D_11; ir_D_12
ir_D_20	Mission Control Center shall interface with Mission Logistic Center		ir_D_21; ir_D_22
ir_D_30	Mission Logistic Center shall interface with ICV		ir_D_31; ir_D_32
ir_D_40	Mission Logistic Center shall interface with Mission Control Center		ir_D_41; ir_D_42
ir_D_50	ORS shall interface with ICV		ir_D_51; ir_D_52; ir_D_53; ir_D_54
ir_A_11	ICV shall be contained within Launch Vehicle	ir_A_10	
ir_A_12	ICV shall transmit data to Launch Vehicle	ir_A_10	
ir_A_21	ICV shall mechanically interface with Cargo Module	ir_A_20	
ir_A_22	ICV shall supply Cargo Module with electric power	ir_A_20	
ir_A_23	ICV shall receive data from Cargo Module	ir_A_20	
ir_A_31	ICV shall transmit data to Lunar Navigation Satellites	ir_A_30	
ir_A_32	ICV shall receive data from Lunar Navigation Satellites	ir_A_30	
ir_A_41	ICV shall mechanically interface with LOP-G	ir_A_40	
ir_A_42	ICV shall transmit data to LOP-G	ir_A_40	
ir_A_43	ICV shall receive data from LOP-G	ir_A_40	
ir_A_51	ICV shall mechanically interface with ORS	ir_A_50	
ir_A_52	ICV shall be supplied with fuel by ORS	ir_A_50	
ir_A_53	ICV shall transmit data to ORS	ir_A_50	
ir_A_54	ICV shall receive data from ORS	ir_A_50	
ir_A_61	ICV shall mechanically interface with MOS	ir_A_60	
ir_A_62	ICV shall transmit data to MOS	ir_A_60	
ir_A_63	ICV shall receive data from MOS	ir_A_60	
ir_A_71	ICV shall transmit data to Mars Communication Satellites	ir_A_70	
ir_A_72	ICV shall receive data from Mars Communication Satellites	ir_A_70	
ir_A_81	ICV shall transmit data to Mars Navigation Satellites	ir_A_80	
ir_A_82	ICV shall receive data from Mars Navigation Satellites	ir_A_80	
ir_A_91	ICV shall transmit data to Mission Control Center	ir_A_90	

Table A.5: Interface Requirements (part 2) - System of Systems

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Interface Requirements			
ir_A_92	ICV shall receive commands from Mission Control Center	ir_A_90	
ir_B_11	ICV shall transmit data to Mission Logistic Center	ir_B_10	
ir_B_12	ICV shall receive commands from Mission Logistic Center	ir_B_10	
ir_B_21	Launch Vehicle shall mechanically interface with ICV	ir_B_20	
ir_B_22	Launch Vehicle shall receive data from ICV	ir_B_20	
ir_B_31	Launch Vehicle shall receive data from Launch Control Station	ir_B_30	
ir_B_32	Launch Vehicle shall transmit data to Launch Control Station	ir_B_30	
ir_B_41	Launch Control Station shall receive data from Launch Vehicle	ir_B_40	
ir_B_42	Launch Control Station shall transmit data to Launch Vehicle	ir_B_40	
ir_B_51	Cargo Module shall mechanically interface with ICV	ir_B_50	
ir_B_52	Cargo Module shall transmit data to ICV	ir_B_50	
ir_B_53	Cargo Module shall be supplied with electric power by ICV	ir_B_50	
ir_B_61	Cargo Module shall mechanically interface with LOP-G	ir_B_60	
ir_B_71	Cargo Module shall mechanically interface with MOS	ir_B_70	
ir_B_81	LOP-G shall mechanically interface with ICV	ir_B_80	
ir_B_82	LOP-G shall receive data from ICV	ir_B_80	
ir_B_83	LOP-G shall transmit data to ICV	ir_B_80	
ir_B_91	LOP-G shall mechanically interface with Cargo Module	ir_B_90	
ir_C_11	Lunar Navigation Satellites shall receive data from ICV	ir_C_10	
ir_C_12	Lunar Navigation Satellites shall transmit data to ICV	ir_C_10	
ir_C_21	Mars Navigation Satellites shall receive data from ICV	ir_C_20	
ir_C_22	Mars Navigation Satellites shall transmit data to ICV	ir_C_20	
ir_C_31	MOS shall mechanically interface with ICV	ir_C_30	
ir_C_32	MOS shall receive data from ICV	ir_C_30	
ir_C_33	MOS shall transmit data to ICV	ir_C_30	
ir_C_41	MOS shall mechanically interface with Cargo Module	ir_C_40	
ir_C_51	MOS shall receive data from Mars Communication Satellites	ir_C_50	

Table A.6: Interface Requirements (part 3) - System of Systems

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Interface Requirements			
ir_C_52	MOS shall transmit data to Mars Communication Satellites	ir_C_50	
ir_C_61	Mars Communication Satellites shall receive data from ICV	ir_C_60	
ir_C_62	Mars Communication Satellites shall transmit data to ICV	ir_C_60	
ir_C_71	Mars Communication Satellites shall receive data from MOS	ir_C_70	
ir_C_72	Mars Communication Satellites shall transmit data to MOS	ir_C_70	
ir_C_81	Mars Communication Satellites shall receive data from Mission Control Center	ir_C_80	
ir_C_82	Mars Communication Satellites shall transmit data to Mission Control Center	ir_C_80	
ir_C_90	Mission Control Center shall receive data from ICV	ir_C_90	
ir_C_91	Mission Control Center shall transmit commands to ICV	ir_C_90	
ir_D_11	Mission Control Center shall receive data from Mars Communication Satellites	ir_D_10	
ir_D_12	Mission Control Center shall transmit data to Mars Communication Satellites	ir_D_10	
ir_D_21	Mission Control Center shall receive data from Mission Logistic Center	ir_D_20	
ir_D_22	Mission Control Center shall transmit data to Mission Logistic Center	ir_D_20	
ir_D_31	Mission Logistic Center shall receive data from ICV	ir_D_30	
ir_D_32	Mission Logistic Center shall transmit commands to ICV	ir_D_30	
ir_D_41	Mission Logistic Center shall receive data from Mission Control Center	ir_D_40	
ir_D_42	Mission Logistic Center shall transmit data to Mission Control Center	ir_D_40	
ir_D_51	Orbital Refuelling System shall mechanically interface with ICV	ir_D_50	
ir_D_52	Orbital Refuelling System shall receive data from ICV	ir_D_50	
ir_D_53	Orbital Refuelling System shall transmit data to ICV	ir_D_50	
ir_D_54	Orbital Refuelling System shall supply ICV with fuel	ir_D_50	

Table A.7: Interface Requirements (part 4) - System of Systems

A.3 System Requirements

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Functional Requirements			
fr_2-111-000	ICV shall provide spacecraft propulsion	fr_2-110-000	fr_2-111-100
fr_2-112-000	ICV shall provide propellant management capabilities	fr_2-110-000	fr_2-112-100
fr_2-113-000	ICV shall provide navigation capabilities	fr_2-110-000	fr_2-113-100
fr_2-114-000	ICV shall provide guidance capabilities	fr_2-110-000	fr_2-114-100
fr_2-115-000	ICV shall provide control capabilities	fr_2-110-000	fr_2-115-100
fr_2-116-000	ICV shall provide power management capabilities	fr_2-110-000	fr_2-116-100
fr_2-117-000	ICV shall provide thermal control capabilities	fr_2-110-000	fr_2-117-100
fr_2-118-000	ICV shall provide environmental protection capabilities	fr_2-110-000	fr_2-118-100
fr_2-119-1-000	ICV shall provide data handling capabilities	fr_2-110-000	fr_2-119-1-100
fr_2-119-2-000	ICV shall provide electronic inputs distribution	fr_2-110-000	fr_2-119-2-100
fr_2-119-3-000	ICV shall provide structural integrity	fr_2-110-000	fr_2-119-3-100
fr_2-119-4-000	ICV shall provide structural support capabilities	fr_2-110-000	fr_2-119-4-100
fr_2-119-5-000	ICV shall provide data communication with orbit elements	fr_2-110-000	fr_2-119-5-100
fr_3-311-000	ICV shall receive data from ground	fr_3-310-000	fr_3-311-100
fr_3-312-000	ICV shall transmit data to ground	fr_3-310-000	fr_3-312-100
fr_3-211-000	ICV shall provide structural support to on-orbit refueling	fr_3-210-000	fr_3-211-100
fr_3-212-000	ICV shall provide fluidic support to on-orbit refueling	fr_3-210-000	fr_3-212-100

Table A.8: Functional Requirements - System

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Functional Requirements - Refinement			
fr_2-111-100	PROP shall provide spacecraft propulsion	fr_2-111-000	fr_2-111-120
fr_2-112-100	PROP shall provide propellant management capabilities	fr_2-112-000	fr_2-112-110; fr_2-112-120
fr_2-113-100	AOCS shall provide navigation capabilities	fr_2-113-000	fr_2-113-110; fr_2-113-120; fr_2-113-130; fr_2-113-140
fr_2-114-100	AOCS shall provide guidance capabilities	fr_2-114-000	fr_2-114-110; fr_2-114-120; fr_2-114-130
fr_2-115-100	AOCS shall provide control capabilities	fr_2-115-000	fr_2-115-110; fr_2-115-120; fr_2-115-130; fr_2-115-140
fr_2-116-100	EPS shall provide power management capabilities	fr_2-116-000	fr_2-116-110; fr_2-116-120; fr_2-116-130; fr_2-116-140
fr_2-117-100	TCS shall provide thermal control capabilities	fr_2-117-000	fr_2-117-110; fr_2-117-120; fr_2-117-130; fr_2-117-140; fr_2-117-150; fr_2-117-160; fr_2-117-170
fr_2-118-100	S&M shall provide environmental protection capabilities	fr_2-118-000	fr_2-118-110; fr_2-118-120
fr_2-119-1-100	DMS shall provide data handling capabilities	fr_2-119-1-000	fr_2-119-1-110; fr_2-119-1-120; fr_2-119-1-130; fr_2-119-1-140; fr_2-119-1-150; fr_2-119-1-160; fr_2-119-1-170; fr_2-119-1-180; fr_2-119-1-190; fr_2-119-1-190-1
fr_2-119-2-100	HARN shall provide electronic inputs distribution	fr_2-119-2-000	fr_2-119-2-110; fr_2-119-2-120; fr_2-119-2-130
fr_2-119-3-100	S&M shall provide structural integrity	fr_2-119-3-000	fr_2-119-3-110; fr_2-119-3-120; fr_2-119-3-130
fr_2-119-4-100	S&M shall provide structural support capabilities	fr_2-119-4-000	fr_2-119-4-110; fr_2-119-4-120; fr_2-119-4-130
fr_2-119-5-100	TT&C shall provide data communication with orbit elements	fr_2-119-5-000	fr_2-119-5-110; fr_2-119-5-120; fr_2-119-5-130; fr_2-119-5-140; fr_2-119-5-160
fr_3-311-100	TT&C shall receive data from ground	fr_3-311-000	fr_3-311-110; fr_3-311-120; fr_3-311-130
fr_3-312-100	TT&C shall transmit data to ground	fr_3-312-000	fr_3-312-110; fr_3-312-120; fr_3-312-130; fr_3-312-140; fr_3-312-150
fr_3-211-100	REF shall provide structural support to on-orbit refueling	fr_3-211-000	fr_3-211-110
fr_3-212-100	REF shall provide fluidic support to on-orbit refueling	fr_3-212-000	fr_3-211-110; fr_3-212-110; fr_3-212-120; fr_3-212-130; fr_3-212-140
Configuration Requirements			
cr_4	The ICV shall consist of PROP, AOCS, EPS, DMS, TT&C, TCS, S&M, REF and HARN		

Table A.9: Functional Requirements Refinement and Configuration Requirements - System

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Interface Requirements			
ir_E_10	EPS shall interface with AOCS		ir_E_11
ir_E_20	EPS shall interface with TCS		ir_E_21
ir_E_30	EPS shall interface with PROP		ir_E_31
ir_E_40	EPS shall interface with REF		ir_E_41
ir_E_50	EPS shall interface with TT&C		ir_E_51
ir_E_60	EPS shall interface with DMS		ir_E_61; ir_E_62; ir_E_63
ir_E_70	EPS shall interface with S&M		ir_E_71
ir_E_80	EPS shall interface with HARN		ir_E_81; ir_E_82
ir_E_90	AOCS shall interface with EPS		ir_E_91
ir_F_10	AOCS shall interface with DMS		ir_F_11; ir_F_12
ir_F_20	AOCS shall interface with S&M		ir_F_21
ir_F_30	AOCS shall interface with HARN		ir_F_31; ir_F_32; ir_F_33
ir_F_40	TCS shall interface with EPS		ir_F_41
ir_F_50	TCS shall interface with DMS		ir_F_51; ir_F_52
ir_F_60	TCS shall interface with S&M		ir_F_61
ir_F_70	TCS shall interface with HARN		ir_F_71; ir_F_72; ir_F_73
ir_F_80	PROP shall interface with EPS		ir_F_81
ir_F_90	PROP shall interface with REF		ir_F_91
ir_G_10	PROP shall interface with DMS		ir_G_11; ir_G_12
ir_G_20	PROP shall interface with S&M		ir_G_21
ir_G_30	PROP shall interface with HARN		ir_G_31; ir_G_32; ir_G_33
ir_G_40	REF shall interface with EPS		ir_G_41
ir_G_50	REF shall interface with PROP		ir_G_51; ir_G_52
ir_G_60	REF shall interface with DMS		ir_G_61
ir_G_70	REF shall interface with S&M		ir_G_71
ir_G_80	REF shall interface with HARN		ir_G_81; ir_G_82; ir_G_83
ir_G_90	TT&C shall interface with EPS		ir_G_91
ir_H_10	TT&C shall interface with DMS		ir_H_11; ir_H_12
ir_H_20	TT&C shall interface with S&M		ir_H_21
ir_H_30	TT&C shall interface with HARN		ir_H_31; ir_H_32; ir_H_33
ir_H_40	DMS shall interface with AOCS		ir_H_41; ir_H_42
ir_H_50	DMS shall interface with TCS		ir_H_51; ir_H_52
ir_H_60	DMS shall interface with PROP		ir_H_61; ir_H_62
ir_H_70	DMS shall interface with REF		ir_H_71; ir_H_72
ir_H_80	DMS shall interface with EPS		ir_H_81; ir_H_82; ir_H_83
ir_H_90	DMS shall interface with TT&C		ir_H_91; ir_H_92

Table A.10: Interface Requirements (part 1) - System

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Interface Requirements			
ir_I_10	DMS shall interface with S&M		ir_I_11
ir_I_20	DMS shall interface with HARN		ir_I_21; ir_I_22; ir_I_23; ir_I_24; ir_I_25
ir_I_30	S&M shall interface with AOCS		ir_I_31
ir_I_40	S&M shall interface with TCS		ir_I_41
ir_I_50	S&M shall interface with PROP		ir_I_51
ir_I_60	S&M shall interface with REF		ir_I_61
ir_I_70	S&M shall interface with EPS		ir_I_71
ir_I_80	S&M shall interface with TT&C		ir_I_81
ir_I_90	S&M shall interface with DMS		ir_I_91
ir_J_10	S&M shall interface with HARN		ir_J_11
ir_J_20	HARN shall interface with AOCS		ir_J_21; ir_J_22; ir_J_23
ir_J_30	HARN shall interface with TCS		ir_J_31; ir_J_32; ir_J_33
ir_J_40	HARN shall interface with PROP		ir_J_41; ir_J_42; ir_J_43
ir_J_50	HARN shall interface with REF		ir_J_51; ir_J_52; ir_J_53
ir_J_60	HARN shall interface with EPS		ir_J_61; ir_J_62
ir_J_70	HARN shall interface with TT&C		ir_J_71; ir_J_72
ir_J_80	HARN shall interface with DMS		ir_J_81; ir_J_82
ir_J_90	HARN shall interface with S&M		ir_J_91
ir_E_11	EPS shall provide electric power to AOCS	ir_E_10	
ir_E_21	EPS shall provide electric power to TCS	ir_E_20	
ir_E_31	EPS shall provide electric power to PROP	ir_E_30	
ir_E_41	EPS shall provide electric power to REF	ir_E_40	
ir_E_51	EPS shall provide electric power to TT&C	ir_E_50	
ir_E_61	EPS shall provide electric power to DMS	ir_E_60	
ir_E_62	EPS shall transmit telemetry and housekeeping data to DMS	ir_E_60	
ir_E_63	EPS shall receive command data from DMS	ir_E_60	
ir_E_71	EPS shall be structurally supported by S&M	ir_E_70	
ir_E_81	EPS shall be provided with commands through HARN	ir_E_80	
ir_E_82	EPS shall transmit telemetry through HARN	ir_E_80	
ir_E_91	AOCS shall be supplied with electrical power by EPS	ir_E_90	
ir_F_11	AOCS shall transmit telemetry and housekeeping data to DMS	ir_F_10	
ir_F_12	AOCS shall receive command data from DMS	ir_F_10	
ir_F_21	AOCS shall be structurally supported by S&M	ir_F_20	
ir_F_31	AOCS shall be provided with commands through HARN	ir_F_30	
ir_F_32	AOCS shall transmit telemetry through HARN	ir_F_30	
ir_F_33	AOCS shall be provided with electrical power through HARN	ir_F_30	

Table A.11: Interface Requirements (part 2) - System

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Interface Requirements			
ir_F_41	TCS shall be supplied with electrical power by EPS	ir_F_40	
ir_F_51	TCS shall transmit telemetry and housekeeping data to DMS	ir_F_50	
ir_F_52	TCS shall receive command data from DMS	ir_F_50	
ir_F_61	TCS shall be structurally supported by S&M	ir_F_60	
ir_F_71	TCS shall be provided with commands through HARN	ir_F_70	
ir_F_72	TCS shall transmit telemetry through HARN	ir_F_70	
ir_F_73	TCS shall be provided with electrical power through HARN	ir_F_70	
ir_F_81	PROP shall be supplied with electrical power by EPS	ir_F_80	
ir_F_91	PROP shall be supplied with fuel by REF	ir_F_90	
ir_G_11	PROP shall transmit telemetry and housekeeping data to DMS	ir_G_10	
ir_G_12	PROP shall receive command data from DMS	ir_G_10	
ir_G_21	PROP shall be structurally supported by S&M	ir_G_20	
ir_G_31	PROP shall be provided with commands through HARN	ir_G_30	
ir_G_32	PROP shall transmit telemetry through HARN	ir_G_30	
ir_G_33	PROP shall be provided with electrical power through HARN	ir_G_30	
ir_G_41	REF shall be supplied with electrical power by EPS	ir_G_40	
ir_G_51	REF shall supply PROP with fuel	ir_G_50	
ir_G_52	REF shall transmit telemetry and housekeeping data to DMS	ir_G_60	
ir_G_61	REF shall receive command data from DMS	ir_G_60	
ir_G_71	REF shall be structurally supported by S&M	ir_G_70	
ir_G_81	REF shall be provided with commands through HARN	ir_G_80	
ir_G_82	REF shall transmit telemetry through HARN	ir_G_80	
ir_G_83	REF shall be provided with electrical power through HARN	ir_G_80	
ir_G_91	TT&C shall be supplied with electrical power by EPS	ir_G_90	
ir_H_11	TT&C shall transmit command data to DMS	ir_H_10	
ir_H_12	TT&C shall receive telemetry and housekeeping data from DMS	ir_H_10	
ir_H_21	TT&C shall be structurally supported by S&M	ir_H_20	
ir_H_31	TT&C shall be provided with telemetry through HARN	ir_H_30	
ir_H_32	TT&C shall transmit commands through HARN	ir_H_30	
ir_H_33	TT&C shall be provided with electrical power through HARN	ir_H_30	

Table A.12: Interface Requirements (part 3) - System

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Interface Requirements			
ir_H_81	DMS shall be supplied with electrical power by EPS	ir_H_80	
ir_H_91	DMS shall transmit telemetry and housekeeping data to TT&C	ir_H_90	
ir_H_92	DMS shall receive command data from TT&C	ir_H_90	
ir_I_11	DMS shall be structurally supported by S&M	ir_I_10	
ir_H_41	DMS shall receive telemetry and housekeeping data from AOCS	ir_H_40	
ir_H_51	DMS shall receive telemetry and housekeeping data from TCS	ir_H_50	
ir_H_61	DMS shall receive telemetry and housekeeping data from PROP	ir_H_60	
ir_H_71	DMS shall receive telemetry and housekeeping data from REF	ir_H_70	
ir_H_82	DMS shall receive telemetry and housekeeping data from EPS	ir_H_80	
ir_H_42	DMS shall transmit command data to AOCS	ir_H_40	
ir_H_52	DMS shall transmit command data to TCS	ir_H_50	
ir_H_62	DMS shall transmit command data to PROP	ir_H_60	
ir_H_72	DMS shall transmit command data to REF	ir_H_70	
ir_H_83	DMS shall transmit command data to EPS	ir_H_80	
ir_I_21	DMS shall be provided with commands through HARN	ir_I_20	
ir_I_22	DMS shall transmit telemetry through HARN	ir_I_20	
ir_I_23	DMS shall gather telemetry and housekeeping data through HARN	ir_I_20	
ir_I_24	DMS shall distribute commands through HARN	ir_I_20	
ir_I_25	DMS shall be provided with electrical power through HARN	ir_I_20	
ir_I_31	S&M shall structurally support AOCS	ir_I_30	
ir_I_41	S&M shall structurally support TCS	ir_I_40	
ir_I_51	S&M shall structurally support PROP	ir_I_50	
ir_I_61	S&M shall structurally support REF	ir_I_60	
ir_I_71	S&M shall structurally support EPS	ir_I_70	
ir_I_81	S&M shall structurally support DMS	ir_I_80	
ir_I_91	S&M shall structurally support TT&C	ir_I_90	
ir_J_11	S&M shall structurally support HARN	ir_J_10	
ir_J_91	HARN shall be structurally supported by S&M	ir_J_90	
ir_J_21	HARN shall transmit commands from DMS to AOCS	ir_J_20	
ir_J_31	HARN shall transmit commands from DMS to TCS	ir_J_30	

Table A.13: Interface Requirements (part 4) - System

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Interface Requirements			
ir_J_41	HARN shall transmit commands from DMS to PROP	ir_J_40	
ir_J_51	HARN shall transmit commands from DMS to REF	ir_J_50	
ir_J_61	HARN shall transmit commands from DMS to EPS	ir_J_60	
ir_J_71	HARN shall transmit commands from TT&C to DMS	ir_J_70	
ir_J_81	HARN shall transmit telemetry and housekeeping data from DMS to TT&C	ir_J_80	
ir_J_22	HARN shall transmit telemetry and housekeeping data from AOCS to DMS	ir_J_20	
ir_J_32	HARN shall transmit telemetry and housekeeping data from TCS to DMS	ir_J_30	
ir_J_42	HARN shall transmit telemetry and housekeeping data from PROP to DMS	ir_J_40	
ir_J_52	HARN shall transmit telemetry and housekeeping data from REF to DMS	ir_J_50	
ir_J_62	HARN shall transmit telemetry and housekeeping data from EPS to DMS	ir_J_60	
ir_J_23	HARN shall conduct electric power from EPS to AOCS	ir_J_20	
ir_J_33	HARN shall conduct electric power from EPS to TCS	ir_J_30	
ir_J_43	HARN shall conduct electric power from EPS to PROP	ir_J_40	
ir_J_53	HARN shall conduct electric power from EPS to REF	ir_J_50	
ir_J_72	HARN shall conduct electric power from EPS to TT&C	ir_J_70	
ir_J_82	HARN shall conduct electric power from EPS to DMS	ir_J_80	

Table A.14: Interface Requirements (part 5) - System

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Performance Requirements			
per-PROP_10	PROP shall provide TBD Ns of total impulse	fr_2-111-100	
per-PROP_20	PROP shall provide TBD N of thrust level	fr_2-111-100	
per-PROP_30	PROP shall manage TBD kg of propellants	fr_2-112-100	
per-AOCS_10	AOCS shall provide solar arrays and antennas pointing	fr_2-115-100	
per-AOCS_20	AOCS shall provide TBD° of control accuracy	fr_2-115-100	
per-AOCS_30	AOCS shall provide TBD rad/s speed of response	fr_2-115-100	
per-AOCS_40	AOCS shall provide TBD Nm of torque capability	fr_2-115-100	
per-AOCS_50	AOCS shall counteract TBD Nm disturbance torques	fr_2-115-100	
per-EPS_10	EPS shall provide power to operate the equipment in compliance with power requirements for each mission phase	fr_2-116-100	
per-EPS_20	EPS shall provide protection against short circuits and fault isolations	fr_2-116-100	
per-TCS_10	TCS shall maintain equipment within operative temperatures	fr_2-117-100	
per-TCS_20	TCS shall cope with the thermal needs of the ICV subsystems as required at any mission phase	fr_2-117-100	
per-TCS_30	TCS shall cope with the space environment throughout the mission	fr_2-117-100	
per-TT&C_10	TT&C shall receive data at a rate of TBD bit/s from orbit elements	fr_2-119-5-100	
per-TT&C_20	TT&C shall transmit data at a rate of TBD bit/s to orbit elements	fr_2-119-5-100	
per-TT&C_30	TT&C shall detect signal from orbit elements within TBD allowable error rate	fr_2-119-5-100	
per-TT&C_40	TT&C shall receive data at a rate of TBD bit/s from ground	fr_3-311-100	
per-TT&C_50	TT&C shall downlink data at a rate of TBD bit/s	fr_3-312-100	
per-TT&C_60	TT&C shall detect signal from ground within TBD allowable error rate	fr_3-311-100	
per-TT&C_70	TT&C shall operate within TBD frequency range	fr_2-119-5-100; fr_3-311-100; fr_3-312-100	

Table A.15: Performance Requirements (part 1) - System

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Performance Requirements			
per-DMS_10	DMS shall cope with data transfer and storage requirements of the ICV subsystems at any mission phase	fr_2-119-1-100	
per-DMS_20	DMS shall transmit data at rates that supports command and telemetry requirements at any mission phase	fr_2-119-1-100	
per-HARN_10	HARN shall dissipate power not exceeding TBD % of operating power	fr_2-119-2-100	
per-HARN_20	HARN shall be compliant with voltage drop requirements	fr_2-119-2-100	
per-HARN_30	HARN shall ensure compatibility for communication to devices onboard the ICV	fr_2-119-2-100	
per-S&M_10	S&M shall be able to withstand a maximum axial load factor of TBD g and a maximum lateral load factor of TBD g	fr_2-119-3-100	
per-S&M_20	S&M shall guarantee fundamental frequencies of the S/C within the requirements of the Launch Vehicle to avoid dynamic coupling	fr_2-119-3-100	
per-S&M_30	S&M shall support the mechanical static and dynamic loads encountered during ICV entire lifetime, including: ground operations, launch, deployment and on-orbit operations.	fr_2-119-3-100	
per-S&M_40	S&M shall be able to survive ground, launch and on-orbit environments	fr_2-118-100	
per-S&M_50	S&M shall cope with components physical and interface requirements	fr_2-119-4-100	
per-S&M_60	S&M shall cope with components requirements for rigidity and thermoelastic distortion	fr_2-119-4-100	
per-REF_10	REF shall be able to afford a maximum force of TBD N and a maximum torque of TBD Nm	fr_3-211-100	
per-REF_20	REF shall ensure sealing between the ICV and the ORS	fr_3-211-100	
per-REF_30	REF shall ensure correct couplings between the ICV and the ORS	fr_3-212-100	

Table A.16: Performance Requirements (part 2) - System

A.4 Subsystems Requirements

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Functional Requirements			
fr_2-111-110	PROP shall provide electric power conditioning and control	fr_2-111-100	fr_2-111-112
fr_2-111-120	PROP shall provide thrust	fr_2-111-100	fr_2-111-112
fr_2-112-110	PROP shall store propellant	fr_2-112-100	fr_2-112-111
fr_2-112-120	PROP shall distribute propellant	fr_2-112-100	fr_2-112-121
fr_2-113-110	AOCS shall provide data for orbit determination	fr_2-113-100	fr_2-113-111
fr_2-113-120	AOCS shall provide data for attitude determination	fr_2-113-100	fr_2-113-121
fr_2-113-130	AOCS shall provide orbit determination	fr_2-113-100	fr_2-113-131
fr_2-113-140	AOCS shall provide attitude determination	fr_2-113-100	fr_2-113-141
fr_2-114-110	AOCS shall provide orbit propagation	fr_2-114-100	fr_2-114-111
fr_2-114-120	AOCS shall provide reference attitude determination	fr_2-114-100	fr_2-114-121
fr_2-114-130	AOCS shall determinate reference trajectory and velocity profile	fr_2-114-100	fr_2-114-131
fr_2-115-110	AOCS shall control position	fr_2-115-100	fr_2-115-111
fr_2-115-120	AOCS shall control velocity	fr_2-115-100	fr_2-115-121
fr_2-115-130	AOCS shall control attitude	fr_2-115-100	fr_2-115-131
fr_2-115-140	AOCS shall control angular rate	fr_2-115-100	fr_2-115-141
fr_2-116-110	EPS shall generate power	fr_2-116-100	fr_2-116-111
fr_2-116-120	EPS shall store energy	fr_2-116-100	fr_2-116-121
fr_2-116-130	EPS shall distribute power	fr_2-116-100	fr_2-116-131
fr_2-116-140	EPS shall regulate power	fr_2-116-100	fr_2-116-141
fr_2-117-110	TCS shall collect heat	fr_2-117-100	fr_2-117-111
fr_2-117-120	TCS shall transport heat	fr_2-117-100	fr_2-117-121
fr_2-117-130	TCS shall provide thermal insulation	fr_2-117-100	fr_2-117-131
fr_2-117-140	TCS shall provide heat rejection	fr_2-117-100	fr_2-117-141
fr_2-117-150	TCS shall provide local heat sink	fr_2-117-100	fr_2-117-151
fr_2-117-160	TCS shall manage thermal control	fr_2-117-100	fr_2-117-161
fr_2-117-170	TCS shall monitor temperatures	fr_2-117-100	fr_2-117-171

Table A.17: Functional Requirements (part 1) - Subsystems

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Functional Requirements			
fr_2-118-110	S&M shall provide radiation protection	fr_2-118-100	fr_2-118-111
fr_2-118-120	S&M shall provide MMOD protection	fr_2-118-100	fr_2-118-121
fr_2-119-3-110	S&M shall carry ground handling loads	fr_2-119-3-100	fr_2-119-3-111
fr_2-119-3-120	S&M shall carry launch loads	fr_2-119-3-100	fr_2-119-3-121
fr_2-119-3-130	S&M shall carry operational loads	fr_2-119-3-100	fr_2-119-3-131
fr_2-119-4-110	S&M shall provide structural support for components	fr_2-119-4-100	fr_2-119-4-111
fr_2-119-4-120	S&M shall provide structural support for mating operations	fr_2-119-4-100	fr_2-119-4-121
fr_2-119-4-130	S&M shall provide structural support for grasping	fr_2-119-4-100	fr_2-119-4-131
fr_3-211-110	REF shall provide mechanical alignment	fr_3-211-100	fr_3-211-111
fr_3-212-110	REF shall provide fluid coupling	fr_3-212-100	fr_3-212-111
fr_3-212-120	REF shall provide electrical coupling	fr_3-212-100	fr_3-212-121
fr_3-212-130	REF shall transfer propellant	fr_3-212-100	fr_3-212-131
fr_3-212-140	REF shall provide storage for received propellant	fr_3-212-100	fr_3-212-141
fr_2-119-1-110	DMS shall receive commands	fr_2-119-1-100	fr_2-119-1-111
fr_2-119-1-120	DMS shall validate commands	fr_2-119-1-100	fr_2-119-1-121
fr_2-119-1-130	DMS shall process commands	fr_2-119-1-100	fr_2-119-1-131
fr_2-119-1-140	DMS shall store commands	fr_2-119-1-100	fr_2-119-1-141
fr_2-119-1-150	DMS shall distribute commands	fr_2-119-1-100	fr_2-119-1-151
fr_2-119-1-160	DMS shall collect telemetries	fr_2-119-1-100	fr_2-119-1-161
fr_2-119-1-170	DMS shall process telemetries	fr_2-119-1-100	fr_2-119-1-171
fr_2-119-1-180	DMS shall store telemetries	fr_2-119-1-100	fr_2-119-1-181
fr_2-119-1-190	DMS shall process mission data	fr_2-119-1-100	fr_2-119-1-191
fr_2-119-1-190-1	DMS shall store mission data	fr_2-119-1-100	fr_2-119-1-191-1
fr_2-119-5-110	TT&C shall provide pointing for receiving	fr_2-119-5-100	fr_2-119-5-111
fr_2-119-5-120	TT&C shall receive data from orbit elements	fr_2-119-5-100	fr_2-119-5-121
fr_2-119-5-130	TT&C shall elaborate data received from orbit elements	fr_2-119-5-100	fr_2-119-5-131
fr_2-119-5-140	TT&C shall elaborate data to be transmitted to orbit elements	fr_2-119-5-100	fr_2-119-5-141

Table A.18: Functional Requirements (part 2) - Subsystems

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Functional Requirements			
fr_2-119-5-150	TT&C shall provide pointing for transmitting	fr_2-119-5-100	fr_2-119-5-151
fr_2-119-5-160	TT&C shall transmit data to orbit elements	fr_2-119-5-100	fr_2-119-5-161
fr_3-311-110	TT&C shall provide pointing for receiving from ground	fr_3-311-100	fr_3_311-111
fr_3-311-120	TT&C shall receive commands from ground	fr_3-311-100	fr_3_311-121
fr_3-311-130	TT&C shall elaborate commands	fr_3-311-100	fr_3_311-131
fr_3-312-110	TT&C shall provide pointing for transmitting to ground	fr_3-312-100	fr_3_312-111
fr_3-312-120	TT&C shall elaborate telemetries to be transmitted	fr_3-312-100	fr_3_312-121
fr_3-312-130	TT&C shall transmit telemetries	fr_3-312-100	fr_3_312-131
fr_3-312-140	TT&C shall elaborate mission data to be transmitted	fr_3-312-100	fr_3_312-141
fr_3-312-150	TT&C shall transmit mission data	fr_3-312-100	fr_3_312-151
fr_2-119-2-110	HARN shall distribute electric power	fr_2-119-2-100	fr_2_119-2-111
fr_2-119-2-120	HARN shall distribute command data	fr_2-119-2-100	fr_2_119-2-121
fr_2-119-2-130	HARN shall distribute telemetries	fr_2-119-2-100	fr_2_119-2-131

Table A.19: Functional Requirements (part 3) - Subsystems

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Functional Requirements - Refinement			
fr_2-111-111	PPU shall provide electric power conditioning and control	fr_2-111-110	
fr_2-111-112	Thruster Units shall provide thrust	fr_2-111-120	
fr_2-112-111	Fuel tanks shall store propellant	fr_2-112-110	
fr_2-112-121	Feeding system shall distribute propellant	fr_2-112-120	
fr_2-113-111	Orbit sensors shall provide data for orbit determination	fr_2-113-110	
fr_2-113-121	Attitude sensors shall provide data for attitude determination	fr_2-113-120	
fr_2-113-131	AOCS OBC shall provide orbit determination	fr_2-113-130	
fr_2-113-141	AOCS OBC shall provide attitude determination	fr_2-113-140	
fr_2-114-111	AOCS OBC shall provide orbit propagation	fr_2-114-110	
fr_2-114-121	AOCS OBC shall provide reference attitude determination	fr_2-114-120	
fr_2-114-131	AOCS OBC shall determinate reference trajectory and velocity profile	fr_2-114-130	
fr_2-115-111	AOCS actuators shall control position	fr_2-115-110	
fr_2-115-121	AOCS actuators shall control velocity	fr_2-115-120	

Table A.20: Functional Requirements Refinement (part 1) - Subsystems

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Functional Requirements - Refinement			
fr_2-116-111	Solar arrays shall generate power	fr_2-116-110	
fr_2-116-121	Batteries shall store energy	fr_2-116-120	
fr_2-116-131	PCDU shall distribute power	fr_2-116-130	
fr_2-116-141	PCDU shall regulate power	fr_2-116-140	
fr_2-117-111	Heat pipes shall collect heat	fr_2-117-110	
fr_2-117-121	Heat pipes shall transport heat	fr_2-117-120	
fr_2-117-131	MLI blankets shall provide thermal insulation	fr_2-117-130	
fr_2-117-141	Radiators shall provide heat rejection	fr_2-117-140	
fr_2-117-151	Electrical heaters shall provide local heat sink	fr_2-117-150	
fr_2-117-161	TCS OBC shall manage thermal control	fr_2-117-160	
fr_2-117-171	Temperature sensors shall monitor temperatures	fr_2-117-170	
fr_2-118-111	Radiation shields shall provide radiation protection	fr_2-118-110	
fr_2-118-121	MDPS panels shall provide MMOD protection	fr_2-118-120	
fr_2-119-3-111	Primary structure shall carry ground handling loads	fr_2-119-3-110	
fr_2-119-3-121	Primary structure shall carry launch loads	fr_2-119-3-120	
fr_2-119-3-131	Primary structure shall carry operational loads	fr_2-119-3-130	
fr_2-119-4-111	Secondary structure shall provide structural support for components	fr_2-119-4-110	
fr_2-119-4-121	Docking I/F shall provide structural support for mating operations	fr_2-119-4-120	
fr_2-119-4-131	Grasping I/F shall provide structural support for grasping	fr_2-119-4-130	
fr_3-211-111	Fluid Plane shall provide mechanical alignment	fr_3-211-110	
fr_3-212-111	Fluid couplings shall provide fluid coupling	fr_3-212-110	
fr_3-212-121	Electrical connector shall provide electrical coupling	fr_3-212-120	
fr_3-212-131	Refueling valves shall transfer propellant	fr_3-212-130	
fr_3-212-141	Refueling tanks shall provide storage for received propellant	fr_3-212-140	
fr_2-119-1-111	Commands decoder shall receive commands	fr_2-119-1-110	
fr_2-119-1-121	Commands decoder shall validate commands	fr_2-119-1-120	
fr_2-119-1-131	OBC shall process commands	fr_2-119-1-130	
fr_2-119-1-141	Data Storage Unit shall store commands	fr_2-119-1-140	
fr_2-119-1-151	RIU shall distribute commands	fr_2-119-1-150	
fr_2-119-1-161	RIU shall collect telemetries	fr_2-119-1-160	

Table A.21: Functional Requirements Refinement (part 2) - Subsystems

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Functional Requirements - Refinement			
fr_2-119-1-171	OBC shall process telemetries	fr_2-119-1-170	
fr_2-119-1-181	Data Storage Unit shall store telemetries	fr_2-119-1-180	
fr_2-119-1-191	OBC shall process mission data	fr_2-119-1-190	
fr_2-119-1-191-1	Data Storage Unit shall store mission data	fr_2-119-1-190-1	
fr_2-119-5-111	Auto-tracking equipment shall provide pointing for receiving	fr_2-119-5-110	
fr_2-119-5-121	Antennas shall receive data from orbit elements	fr_2-119-5-120	
fr_2-119-5-131	Receiver shall elaborate data received from orbit elements	fr_2-119-5-130	
fr_2-119-5-141	Transmitter shall elaborate data to be transmitted to orbit elements	fr_2-119-5-140	
fr_2-119-5-151	Auto-tracking equipment shall provide pointing for transmitting	fr_2-119-5-150	
fr_2-119-5-161	Antennas shall transmit data to orbit elements	fr_2-119-5-160	
fr_3-311-111	Auto-tracking equipment shall provide pointing for receiving from ground	fr_3-311-110	
fr_3-311-121	Antennas shall receive commands from ground	fr_3-311-120	
fr_3-311-131	Receiver shall elaborate commands	fr_3-311-130	
fr_3-312-111	Auto-tracking equipment shall provide pointing for transmitting to ground	fr_3-312-110	
fr_3-312-121	Transmitter shall elaborate telemetries to be transmitted	fr_3-312-120	
fr_3-312-131	Antennas shall transmit telemetries	fr_3-312-130	
fr_3-312-141	Transmitter shall elaborate mission data to be transmitted	fr_3-312-140	
fr_3-312-151	Antennas shall transmit mission data	fr_3-312-150	
fr_2-119-2-111	Electric power harness shall distribute electric power	fr_2-119-2-110	
fr_2-119-2-121	Data bus shall distribute command data	fr_2-119-2-120	
fr_2-119-2-131	Data bus shall distribute telemetries	fr_2-119-2-130	

Table A.22: Functional Requirements Refinement (part 3) - Subsystems

REQ ID	DESCRIPTION	DEPENDS ON	AFFECTS
Configuration Requirements			
cr_5	The PROP shall consist of PPU, Thruster Units, fuel tanks and feeding system		
cr_6	The AOCS shall consist of orbit sensors, attitude sensors, AOCS actuators and AOCS OBC		
cr_7	The EPS shall consist of solar arrays, batteries and PCDU		
cr_8	The TCS shall consist of heat pipes, MLI blankets, radiators, electrical heaters, TCS OBC, and temperature sensors		
cr_9	The S&M shall consist of radiation shields, MDPS panels, primary structure, secondary structure, docking I/F and grasping I/F		
cr_10	The REF shall consist of Fluid Plane, fluid couplings, electrical connector, refueling valves and refueling tanks		
cr_11	The DMS shall consist of commands decoder, OBC, Data Storage Unit and RIU		
cr_12	The TT&C shall consist of antennas, receiver, transmitter and auto-tracking equipment		
cr_13	The HARN shall consist of data bus and electric power harness		

Table A.23: Configuration Requirements - Subsystems

A.5 Environmental and Operational Requirements

A.5.1 Scenario 2D

REQ ID	DESCRIPTION
Environmental Requirements	
Launch	
er-LAUNCH_10	ICV shall withstand launch environment during launch
er-LAUNCH_20	ICV shall be able to sustain launch loads during launch
er-LAUNCH_30	ICV shall be able to sustain launch vibration during launch
er-LAUNCH_40	ICV shall limit heat leak/gain to/from natural environment during launch
er-LAUNCH_50	ICV shall withstand TBD temperature range during launch
er-LAUNCH_60	ICV shall be able to sustain separation shock during launch
Early Operations	
er-EO_10	ICV shall withstand LEO environment during early operations
er-EO_20	ICV shall be able to sustain operational loads during early operations
er-EO_30	ICV shall limit heat leak/gain to/from natural environment during early operations
er-EO_40	ICV shall be able to operate within TBD temperature range during early operations
er-EO_50	ICV shall withstand neutral atmosphere bombardment during early operations
er-EO_60	ICV shall withstand atmosphere particles contamination during early operations
er-EO_70	ICV shall limit charge particles effect on equipment during early operations
er-EO_80	ICV shall be able to sustain a TBD radiation dose during early operations
er-EO_90	ICV shall be compliant with a TBD probability of potential damage from micrometeoroids and orbital debris impact during early operations
EOR to LOP-G	
er-EOR1_10	ICV shall withstand EOR environment during EOR from LEO to LOP-G
er-EOR1_20	ICV shall be able to sustain operational loads during EOR from LEO to LOP-G
er-EOR1_30	ICV shall limit heat leak/gain to/from natural environment during EOR from LEO to LOP-G
er-EOR1_40	ICV shall be able to operate within TBD temperature range during EOR from LEO to LOP-G
er-EOR1_50	ICV shall be able to sustain a TBD radiation dose during EOR from LEO to LOP-G
er-EOR1_60	ICV shall limit radiation effect on equipment during EOR from LEO to LOP-G
er-EOR1_70	ICV shall be compliant with a TBD probability of potential damage from micrometeoroids and orbital debris during EOR from LEO to LOP-G
er-EOR1_80	ICV shall be compatible with TBD amount of plume impingement from thrusters during EOR from LEO to LOP-G
Rendezvous and docking with Cargo Module	
er-R&D-LOP-G1_10	ICV shall be compliant with the Cargo Module docking mechanism
er-R&D-LOP-G1_20	ICV shall limit loads during docking to Cargo Module
er-R&D-LOP-G1_30	ICV shall absorb shocks during docking to Cargo Module
er-R&D-LOP-G1_40	ICV shall be able to compensate TBD misalignments with Cargo Module
er-R&D-LOP-G1_50	ICV shall not exceed TBD contact velocity while docking to Cargo Module

Table A.24: Environmental Requirements (part 1) - Scenario 2D

REQ ID	DESCRIPTION
Environmental Requirements	
Undocking from LOP-G	
er-UNDOCK-LOP-G_10	ICV shall limit loads while undocking the Cargo Module from LOP -G
er-UNDOCK-LOP-G_20	ICV shall absorb shocks while undocking the Cargo Module from LOP -G
er-UNDOCK-LOP-G_30	ICV shall maintain TBD separation velocity while undocking the Cargo Module from LOP -G
LOP-G-ORS EOR	
er-EOR2_10	ICV shall withstand EOR environment during EOR from LOP -G to ORS
er-EOR2_20	ICV shall be able to sustain operational loads during EOR from LOP -G to ORS
er-EOR2_30	ICV shall limit heat leak/gain to/from natural environment during EOR from LOP -G to ORS
er-EOR2_40	ICV shall be able to operate within TBD temperature range during EOR from LOP -G to ORS
er-EOR2_50	ICV shall be able to sustain a TBD radiation dose during EOR from LOP -G to ORS
er-EOR2_60	ICV shall limit radiation effect on equipment during EOR from LOP -G to ORS
er-EOR2_70	ICV shall be compliant with a TBD probability of potential damage from micrometeoroids and orbital debris during EOR from LOP -G to ORS
er-EOR2_80	ICV shall be compatible with TBD amount of plume impingement from thrusters during EOR from LOP -G to ORS
Rendezvous and docking with ORS	
er-R&D-ORS_10	ICV shall limit loads during docking to the ORS docking port
er-R&D-ORS_20	ICV shall absorb shocks during docking to the ORS the docking port
er-R&D-ORS_30	ICV shall not exceed TBD contact velocity while docking to the ORS docking port
Refueling	
er-REF_10	ICV shall be compliant with the refueling mechanism crossing Cargo Module
er-REF_20	ICV shall sustain fuel pressure during refueling phase
er-REF_30	ICV shall limit torques and forces during refueling phase
Undocking from ORS	
er-UNDOCK-ORS_10	ICV shall limit loads during undocking from ORS
er-UNDOCK-ORS_20	ICV shall absorb shocks during undocking from ORS
er-UNDOCK-ORS_30	ICV shall maintain TBD separation velocity during undocking from ORS
ORS-MOS EOR	
er-EOR3_10	ICV shall withstand EOR environment during EOR from ORS to MOS
er-EOR3_20	ICV shall be able to sustain operational loads during EOR from ORS to MOS
er-EOR3_30	ICV shall limit heat leak/gain to/from natural environment during EOR from ORS to MOS
er-EOR3_40	ICV shall be able to operate within TBD temperature range during EOR from ORS to MOS
er-EOR3_50	ICV shall be able to sustain a TBD radiation dose during EOR from ORS to MOS
er-EOR3_60	ICV shall limit radiation effect on equipment during EOR from ORS to MOS
er-EOR3_70	ICV shall be compliant with a TBD probability of potential damage from micrometeoroids and orbital debris during EOR from ORS to MOS
er-EOR3_80	ICV shall be compatible with TBD amount of plume impingement from thrusters during EOR from ORS to MOS
Rendezvous and docking with MOS	
er-R&D-MOS_10	ICV shall limit loads while docking the Cargo Module to the MOS docking port
er-R&D-MOS_20	ICV shall absorb shocks while docking the Cargo Module to the MOS docking port
er-R&D-MOS_30	ICV shall not exceed TBD contact velocity while docking the Cargo Module to the MOS docking port

Table A.25: Environmental Requirements (part 2) - Scenario 2D

REQ ID	DESCRIPTION
Environmental Requirements	
Checking and Cargo handling at MOS	
er-C&CH_10	ICV shall maintain attitude while Cargo Module is docked at MOS
er-C&CH_20	ICV shall limit torques and forces while Cargo Module is docked at MOS
Undocking from MOS	
er-UNDOCK-MOS_10	ICV shall limit loads while undocking the Cargo Module from MOS
er-UNDOCK-MOS_20	ICV shall absorb shocks while undocking the Cargo Module from MOS
er-UNDOCK-MOS_30	ICV shall maintain TBD separation velocity while undocking the Cargo Module from MOS
MOS - LOP-G EOR	
er-EOR4_10	ICV shall withstand EOR environment during EOR from MOS to LOP-G
er-EOR4_20	ICV shall be able to sustain operational loads during EOR from MOS to LOP-G
er-EOR4_30	ICV shall limit heat leak/gain to/from natural environment during EOR from MOS to LOP-G
er-EOR4_40	ICV shall be able to operate within TBD temperature range during EOR from MOS to LOP-G
er-EOR4_50	ICV shall be able to sustain a TBD radiation dose during EOR from MOS to LOP-G
er-EOR4_60	ICV shall limit radiation effect on equipment during EOR from MOS to LOP-G
er-EOR4_70	ICV shall be compliant with a TBD probability of potential damage from micrometeoroids and orbital debris during EOR from MOS to LOP-G
er-EOR4_80	ICV shall be compatible with TBD amount of plume impingement from thrusters during EOR from MOS to LOP-G
Rendezvous and docking with LOP-G	
er-R&D-LOP-G2_10	ICV shall limit loads while docking the Cargo Module to the LOP-G docking port
er-R&D-LOP-G2_20	ICV shall absorb shocks while docking the Cargo Module to the LOP-G docking port
er-R&D-LOP-G2_30	ICV shall not exceed TBD contact velocity while docking the Cargo Module to the LOP-G docking port
Logistics, checking and maintenance	
er-LCM_10	ICV shall maintain attitude while Cargo Module is docked at LOP-G
er-LCM_20	ICV shall limit torques and forces while Cargo Module is docked at LOP-G
Berthing and undocking	
er-BER&UNDOCK_10	ICV shall limit loads during berthing and undocking from Cargo Module
er-BER&UNDOCK_20	ICV shall absorb shocks during berthing and undocking from Cargo Module
Relocation to new Cargo Module	
er-RELOC_10	ICV shall be able to sustain robotic arm loads during relocation to new Cargo Module
Docking and release	
er-DOCK&REL_10	ICV shall limit loads during docking and release to new Cargo Module
er-DOCK&REL_20	ICV shall absorb shocks during docking and release to new Cargo Module

Table A.26: Environmental Requirements (part 3) - Scenario 2D

REQ ID	DESCRIPTION
Operational Requirements	
or_A_10	The ICV shall be able to enter in Launch-off mode in the Launch phase
or_A_20	The ICV shall be able to enter in Early Operations mode in the Early Operations phase
or_A_30	The ICV shall be able to enter in EP mode in the "EOR to LOP-G" phase
or_A_40	The ICV shall be able to enter in CP mode in the " Rendezvous and docking with Cargo Module" phase
or_A_50	The ICV shall be able to enter in CP mode in the "Undocking from LOP-G" phase
or_A_60	The ICV shall be able to enter in EP mode in the "EOR to ORS" phase
or_A_70	The ICV shall be able to enter in CP mode in the "Undocking from ORS" phase
or_A_80	The ICV shall be able to enter in EP mode in the "ORS - MOS EOR" phase
or_A_90	The ICV shall be able to enter in CP mode in the "Rendezvous and docking with MOS" phase
or_B_10	The ICV shall be able to enter in Stand-by mode in the "Checking and Cargo handling at MOS" phase
or_B_20	The ICV shall be able to enter in Check mode in the "Checking and Cargo handling at MOS" phase
or_B_30	The ICV shall be able to enter in CP mode in the "Undocking from MOS" phase
or_B_40	The ICV shall be able to enter in EP mode in the "MOS - LOP-G EOR" phase
or_B_50	The ICV shall be able to enter in CP mode in the "Rendezvous and docking with LOP-G" phase
or_B_60	The ICV shall be able to enter in Check mode in the "Logistics, checking and maintenance" phase
or_B_70	The ICV shall be able to enter in Stand-by mode in the "Berthing and undocking" phase
or_B_80	The ICV shall be able to enter in Stand-by mode in the "Relocation to new Cargo Module" phase
or_B_90	The ICV shall be able to enter in Stand-by mode in the "Docking and release" phase
or_C_10	The ICV shall be able to enter in CP mode in the "Undocking from Cargo Module" phase
or_C_20	The ICV shall be able to enter in Disposal mode in the "EOR to graveyard orbit and switch-off" phase

Table A.27: Operational Requirements - Scenario 2D

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