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Simulator design for MMX rover

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KUNGLIGA TEKNISKA HÖGSKOLAN

MASTER THESIS

Simulator Design for the MMX rover

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in the

Aerospace Engineering

department

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Declaration of Authorship

I, Maxime OLIVARI, declare that this thesis titled, "Simulator Design for the MMX rover" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a master degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
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Signed:

Date: 29/06/2020

"Look again at that dot. That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives. [...] Our planet is a lonely speck in the great enveloping cosmic dark. In our obscurity, in all this vastness, there is no hint that help will come from elsewhere to save us from ourselves.

The Earth is the only world known so far to harbor life. There is nowhere else, at least in the near future, to which our species could migrate. Visit, yes. Settle, not yet. Like it or not, for the moment the Earth is where we make our stand."

"It has been said that astronomy is a humbling and character-building experience. There is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world. To me, it underscores our responsibility to deal more kindly with one another, and to preserve and cherish the pale blue dot, the only home we've ever known."

Carl Sagan, Pale Blue Dot, 1994

Sammanfattning

Rymdprojekt involverar speciella strategier i systemdesign som simuleringsteknik. Den franska rymdbyrån använder detta teknikområde för utveckling av ett litet fordon. Baserat på projektdokumentationen och målen frågar denna studie: Vad är simulatorarkitekturen som möjliggör validering av flygprogramvaran inbäddad i rover? Med hänsyn till projektbehov och mjukvara som används leder till en relevant arkitektur som uppfyller projektets mål.

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Abstract

Aerospace Engineering

Master of Science in Engineering

Simulator Design for the MMX rover

by Maxime OLIVARI

An internship fulfilled at

CNES
CENTRE NATIONAL
D'ÉTUDES SPATIALES

Space projects involve particular strategies in system design such as simulation engineering. The french space agency uses this field of engineering in the development of a small vehicle (called rover) aiming to investigate one of the moons of Mars. The creation of this simulation environment starts with the design of its architecture. This study aims to derive this architecture. Based on the project documentation and objectives it asks: What is the simulator architecture that enables the validation of the flight software embedded in the rover ?

The collecting of validation needs from the core team consist a first step that defines the content of the architecture. The training on the simulator development platform used at the french space agency provides the framing of this architecture. Taking into account this two steps lead to a relevant architecture that satisfy the project needs.

Acknowledgements

I would like to thank first Elise Aitier who helped me to get the internship and managed my introduction at Centre National d'Etudes Spatiales - French space agency (CNES). She was my gateway to the Martian Moon eXplorer (MMX) core team and helped me to find relevant information that was necessary for my thesis work.

I'm sincerely grateful for the help I received from Coline Brunner. She helped me in my every day work and was constantly available. I appreciated a lot to work with her and pursue this thesis by her side. Many of our discussions provided me new knowledge on space engineering and space project management. The quality of my thesis is in part due to her consideration for the work I have done. I will keep a good memory of this internship mainly due to her.

I also want to warmly thank Patrick Landrodie, the chief of the simulation department at CNES. He introduced me to the service and made sure that I was feeling comfortable in the team. His knowledge on the space industry and on the various actors of the space industry was precious. He showed me how space engineering can be the place of friendship and human considerations.

Finally I want to express my gratitude to the simulation team with which I had very interesting conversations every day. They were curious about what I was doing and guided me when it was necessary.

Contents

List of Figures

Acronyms

ACS Attitude Control sub-System

AIT Assembling Integration and Testing

BASILES Base d'Application pour Simulateurs et Logiciels d'Etudes de Systèmes complexes - Application base for simulators and softwares of complex systems

CNES Centre National d'Etudes Spatiales - French space agency

DLR Deutsches zentrum für Luft- und Raumfahrt - German Space agency

EDRES Environement de Développement pour la Robotique d'Exploration Spatiale

ESA European Space Agency

FDIR Failure Detection Isolation and Recovery

FPGA Field Programmable Gate Array

HDRM Hold Down and Release Mechanism

HSEM Hardware and Software Events Monitoring

I/F InterFace

JAXA Japan Aerospace eXploration Agency

LVCUGEN Logiciel de Vol Charge Utile GENerique - Genric payload flight software

MASCOT Mobile Asteroid surface SCOut

MECSS Mechanical, Electrical Communication and Separation Subsystem

MMDL Mode Management and Data Load

MMX Martian Moon eXplorer

NASA National Aeronautics and Space Administration

OBC On Board Computer

OBS On Board Software

PCDU Power Control and Distribution Unit

PPS Pulse Per Second

RAX RAman spectrometer for mmX)

RF Radio Frequency

Rx Receiver

S/C SpaceCraft

SLUD Separation Landing Uprighting and Deployment

SMA Shape Memory Alloy

SpW SpaceWire

SVF Software Validation Facility

TC TeleCommand

TM TeleMetry

TOMS Training Operations and Maintenance Simulator

Tx Transmitter

To my grandfather...

Chapter 1

Internship context

1.1 MMX mission

The Martian Moon eXplorer SpaceCraft is a Japanese orbiter aiming to observe the moons of Mars and prepare Japan Aerospace eXploration Agency (JAXA)'s future missions. The JAXA agency has proposed a slot on their MMX mission to the French space agency. With this opportunity, CNES decided to develop a small rover. This rover will be deployed by the MMX S/C from the orbit of Phobos, land and roll on the surface of Phobos shown in figure 1.1. The JAXA will be able to use the data collected by the rover to improve the selection process for their lander landing site location.

FIGURE 1.1: Phobos
[1]

For this mission the French and the German space agencies agreed to collaborate and split the rover design tasks. CNES is responsible for the mechanical and thermal structure of the rover's frame, the power management (solar array, battery pack, and PCDU, the avionics and the electrical network, and will provide the stereo bench and two cameras (WheelCams). The locomotion part (electronics and hardware) will be designed and qualified by the Deutsches zentrum für Luft- und Raumfahrt - German Space agency (DLR) but also two scientific payloads: RAX and MiniRAD, to study the composition of Phobos ground. The integration and testing activities are ensured by CNES except for the locomotion system. CNES is also in charge of the system's flight software development. But some of the navigation part of the on-board software will be developed by the DLR. The CNES has the responsibility for the architecture of process-control and on-board software, thus it will also be responsible for the functional validation of the system. An overall view of the complete system is shown in figure 1.2.

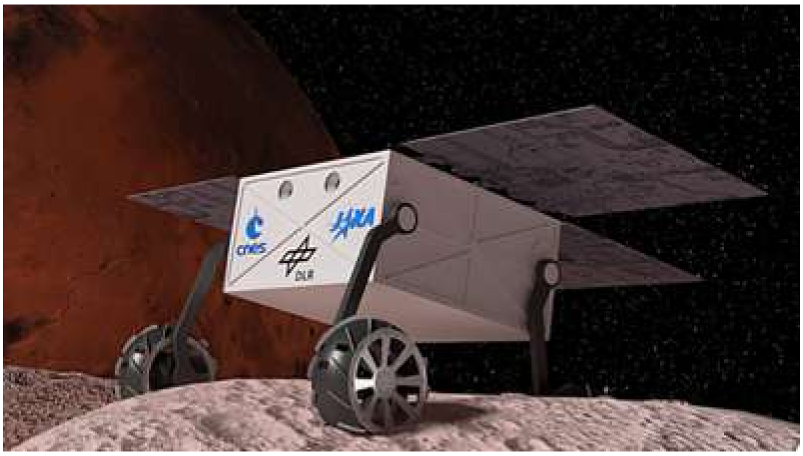

FIGURE 1.2: MMX rover on the surface of Phobos

1.2 MMX rover objectives

> "JAXA has assigned two high level objectives: landing risk mitigation for the MMX S/C and a contribution to the scientific objectives. For CNES and DLR, the rover has also several technological demonstrator ambitions which constitute the real challenge for the robotic."[2]

1.2.1 JAXA's point of view

The first objective is the risk mitigation of the landing site for the MMX lander. This objective will be partly done by taking picture with the rover's stereo bench during its freefall on Phobos, after separation. If later on the rover doesn't succeed to stand up and start the roving mission, we will already be able to provide some pictures of the fall that may be relevant for the MMX mission.

1.2.2 CNES/DLR's point of view

Beside this first objective, the rover will have to complete scientific and technological goals. The JAXA proposed to CNES/DLR three main scientific objectives, and the CNES/DLR collaboration proposed two technological objectives which will be achieved thanks to on-board sub-systems.

Scientific objectives

As it is explain in the report "A rover for the JAXA MMX Mission to Phobos"[3]

> "The Rover will perform:
>
> - Regolith science (e.g. dynamics, mechanical properties like surface strength, cohesion, adhesion; geometrical properties like grain size distribution, porosity),
> - Close-up and high resolution imaging of the surface terrain,
> - Measurements of the mineralogical composition of the surface material (by Raman spectroscopy)
> - Measurements of the mineralogical composition of the surface material (by Raman spectroscopy)
> - Determination of the thermal properties of the surface material (surface temperature, thermal capacity, thermal conductivity)
>
> This will allow determination of the heterogeneity of the surface material and thus will also help defining the landing and sampling strategy. Characterization of the regolith properties shall considerably reduce the risk of the landing (and sampling) of the main S/C, as the touch-down strategy can be adapted accordingly."

In order to complete these scientific objectives, the rover will carry three scientific payloads: RAX, MiniRAD, and two wheel cameras. In order to understand how these systems will contribute to the achievement of the scientific goals, a more detailed description of how they work can be found in the section. 3.2

Technological objectives

In addition to these scientific objectives the MMX rover will have to accomplish technological objectives. The rover having a demonstrator role, these objectives allow to estimate the viability of several technologies on-board.

I. Micro-gravity rolling

   The rover has to roll over a minimum distance of 100 meters on Phobo's ground.

II. Autonomous navigation

   The rover has to be able to detect obstacles and avoid them by getting around them autonomously.

To accomplish these technological objectives the rover is equipped with dedicated locomotion and navigation sub-systems. A more detailed description of these sub-systems can be found in the section 3.2.

The fulfilment of these two categories of objectives will be achieved during the different phases of the mission. They are the following:

- Launch and Cruise (incl. commissioning, health checks),
- Separation-Landing-Upright-Deployment (SLUD) phase (from separation from the main S/C, to descent, bouncing-phase to the quasi-autonomous up-righting and solar generator deployment),
- Phobos commissioning phase, to check the functionality of the Rover, its subsystems and payload,
- Phobos Operational (Driving & Science) Phase with a life-time of > 100 days (including previous commissioning phase) on the surface of Phobos. During this phase [...] instruments will perform measurements at different locations on Phobos surface,
- End of Mission phase (finally passivizing the Rover).[3]

1.3 MMX rover project context

Any space project goes through progressive development stages called phases. They are summed up in figure 1.3.

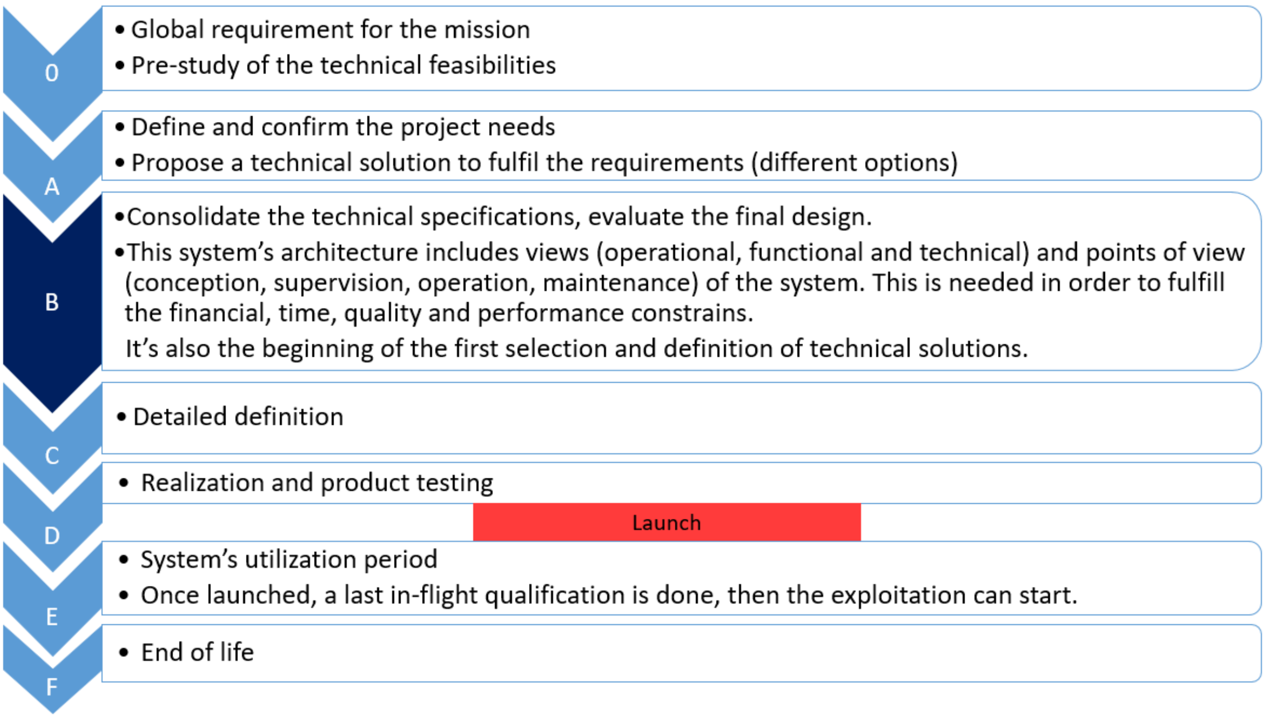

FIGURE 1.3: Project planing in the space industry

The MMX rover project is currently in phase B since the system's architecture is still in discussion.

1.3.1 MMX core team

The MMX core team is composed of several experts working at CNES. They were detached from their original work department to participate at full time to the project. They come from the following departments:

- Avionics,
- Flight software,
- Science,
- Robotics,
- Operations,
- Communication,
- Attitude control.

A precise description of their respective role can be found in section 3.4.

1.3.2 AVI/VS department

This department is in charge of the design of the simulation means and procedures at CNES. It works in close collaboration with the other departments of the agency to design required simulators. The hierarchy from the CNES president to the AVI/VS department is shown in figure 1.4.

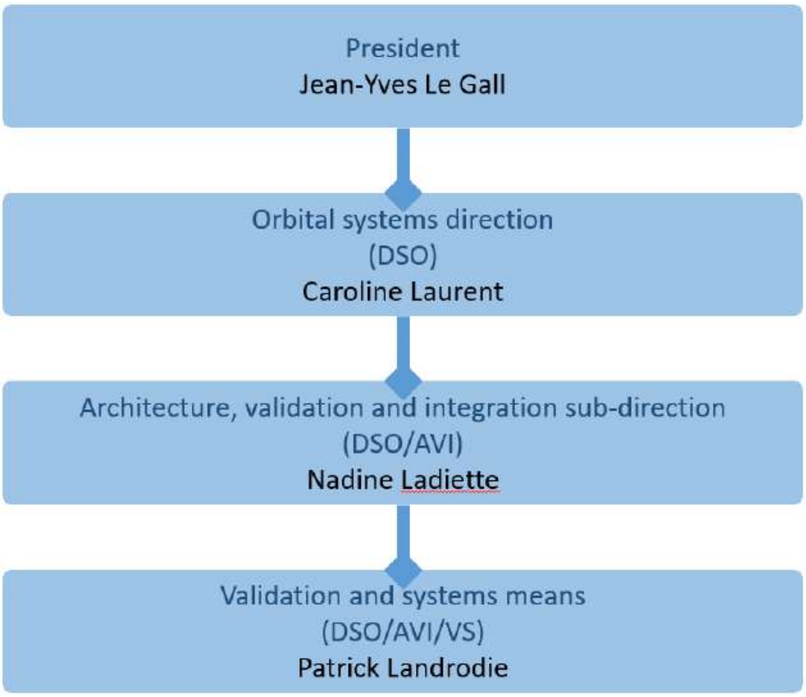

FIGURE 1.4: CNES DSO/AVI/VS organizational chart

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Chapter 2

Internship objectives

2.1 Introduction

> "The software is required to work the very first time flown. Unlike e.g. aircraft systems, there is no opportunity to make prototype flights, where deficiencies can be found and corrected. This leads to strong requirements for software validation, including [...] software validation facilities. "[4]

This quote from the European Space Agency (ESA) introduces one of the main requirements for flight software in the context of a space system.

In order to validate and qualify the different parts of the on-board software, and in order to validate the whole on-board software, the MMX team expressed the need for a simulator. To create this simulator, its role and content need to be specified. Moreover, as the development of a complete space system simulator is a step that can costs a lot of time. Thus the aim of the internship is limited to the production of the simulator architecture only.

Internship overall goal: Produce the architecture of the simulation environment needed to qualify the flight software of the MMX rover On Board Software (OBS).

To fulfill this objective, the internship is organized around three main tasks:

I. The listing of the validation needs from the different members of the team,

II. The acquaintance of the simulation platform used at CNES: Base d'Application pour Simulateurs et Logiciels d'Etudes de Systèmes complexes - Application base for simulators and softwares of complex systems (BASILES),

III. The definition of the simulator architecture taking into account the results of the two previous steps.

These tasks are split in time in a progressive and logical manner. A more detailed description of the content of these three tasks can be found at section 2.3 and an overall view of the time distribution is shown in figure 2.1.

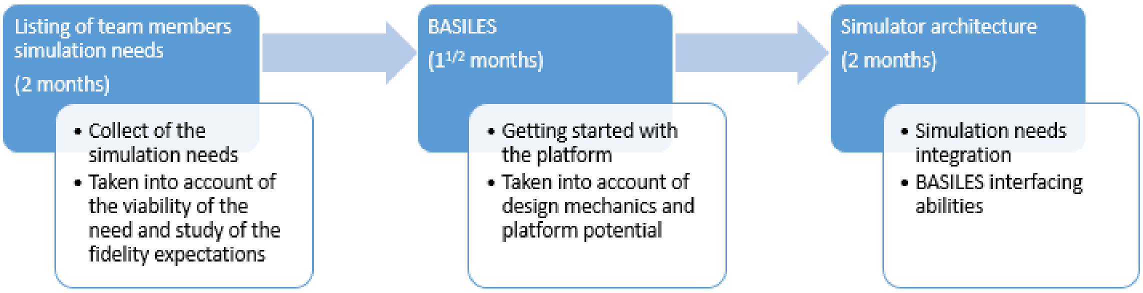

FIGURE 2.1: Time distribution of the different tasks realized during the internship

2.2 Organisation and validation tools

Before the rover can start its mission, there is usually two phases: the unitary validation of each flight software function and the system validation of the flight software in a representative environment. In order to accomplish this objective, the validation office at CNES usually uses a simulation environment which helps to visualize the behavior of the flight software in a controlled environment. The validation office will thus deliver several tools corresponding to different versions of this simulation environment.

2.2.1 Unitary flight software validation

This step aims to confirm that the system software meets the specifications and fulfills its intended purpose. Which means that the system architecture is sufficient and allows the flight software to fulfill all of the mission objectives. This validation step needs a testing environment which will be representative of the real system. At this step the simulation environment is similar to the real system only from a functional point of view. Therefore the team decided that the simulator will be not composed of examples of each sub-systems, but of each functional group. However, the I/F between the flight software and the simulation environment are exactly the same as the ones between the flight software and the real system during the mission. This kind of simulation environment is called a Software Validation Facility also known as SVF.

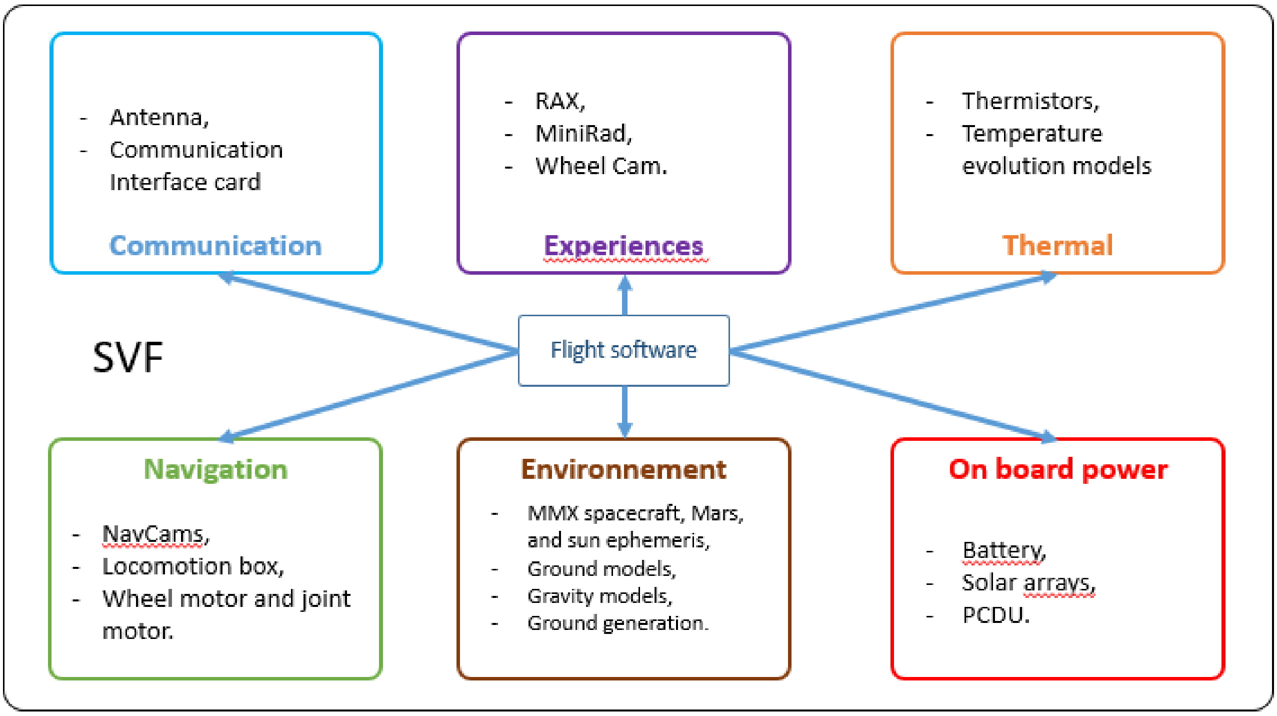

FIGURE 2.2: Structure and operations of a SVF

In this case sub-systems are grouped by functions, the I/F between the flight software and these groups are the same than the ones used during the mission and are showed in figure 2.2.

A first version of this simulation environment is an adaptation for the rover MMX project of a CNES product called HSVF (for Hybrid Simulation Validation Facility). The HSVF is a hybrid validation board (which means that the simulation product uses numerical models that run through the BASILES infrastructure and hardware systems) where it is possible to run the flight software of the MMX rover. The MMX HSVF will be composed of an electronic card comparable to the one on the rover, with the same I/F, and numerical models able to stimulate the nominal behavior of the flight software.

2.2.2 System qualification simulator

The qualification step aims to test the flight software under more realistic conditions. In this simulation environment the models are more accurate and adopt another point of view than in the HSVF. Here the models are not representative of certain functions anymore, but of certain sub-systems which allow to go from a functional study to a system study. This will help to validate the functional chains of the control center and the flight software. This kind of simulation environment is called a Training for Operations and Maintenance Simulator also known as TOMS, its structure is shown in figure 2.3.

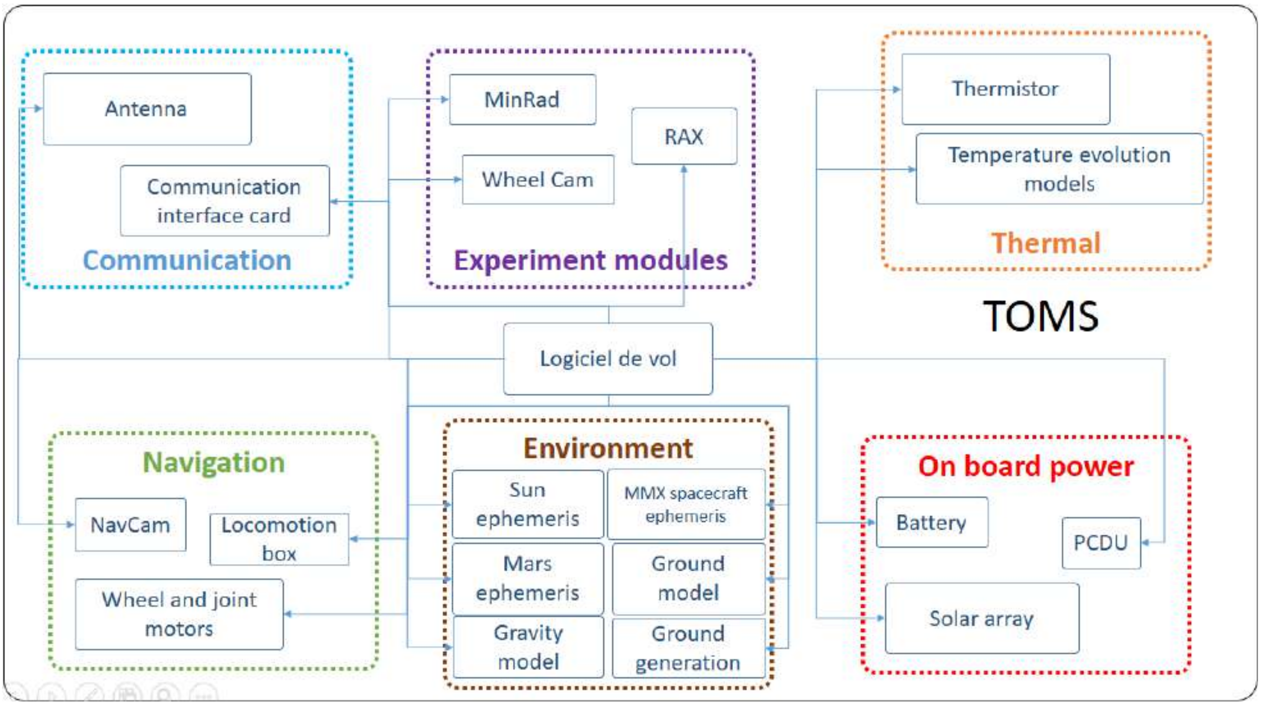

FIGURE 2.3: Structure and operations of a TOMS

Here the different elements of the system are not regrouped by functions anymore but by sub-systems, and all I/F are representative of the reality like for a SVF.

The development of this simulation environment follows different design rules. These rules aim to identify the different functions of the rover that are part of the flight software environment and estimate the needed configuration to include them in the simulation environment.

The demand for the development of a simulator is usually joined by a file called « system validation plan ». This file describes in details what are the tests to run on the system to ensure its viability. It specifies which are the elements to be tested, how they have to be tested, and what are the error margins that can be accepted. But the MMX rover project has a very limited time to finish the conception of the rover and qualify it to fly.

> "The first constraint that applies to the rover project is the overall schedule of the MMX mission.[...] The development of the rover will only last five years, starting nearly from scratch. Indeed, even though CNES and DLR have already contributed to studies on rovers for Mars or for the Moon, none have yet worked on a rover for the moon of Mars."[2]

In fact, MMX is to be launched in 2024, and the CNES core team for the MMX rover started to work full time on the project after the beginning of my internship (December 2019). Thus there is four years left before the launch. In the space industry it is not very common for a project to last less than height years. It is the reason why at this point the « system validation plan » is missing.

The absence of this document is not critical for the conception of the simulator, but it implies that the beginning of the design of the simulator will be based on assumptions (or other relevant documents about the rover MMX system) rather than precise information on the testing procedures. Thus it seems that a study from the system perspective will be needed to understand how the rover works and what kind of test will be relevant for the qualification of the system.

2.3 Internship activities

The previous chapter resumed what are the different products that will be delivered to the MMX rover core team. In order to produce these products, the first step is to design the architecture of the simulation environment. This step is very important for the future development of the simulator. It will be articulated around three main axes:

- Collecting of the simulation needs for every department of the core team,
- Training with the simulation platform BASILES,
- Design of the TOMS architecture.

This section explains briefly what are the main tasks done during the internship. A full description of these tasks follows in the report in chapters 3, 4 and 5.

2.3.1 Job interviews

The objective of job interviews is to clarify which functions or elements should be tested. Thus this means to meet and interview the main participants to the project. Later on these validation needs will be traduced into simulation needs. Moreover, through the validation needs it was important to distinguish three main characteristics of a simulation need:

I. The different sub-systems of the rover impacted by the need,

II. The minimum representativeness in order to satisfy the performance goals,

III. The feasibility of this need in terms of financial and time constraints.

2.3.2 BASILES platform

The simulation means will be developed on a platform called BASILES (Base d'Application pour Simulateurs et Logiciels d'Etude de Systèmes complexes, the French for Application Base for complex Systems Study Simulators and Software). It is a development platform for complex systems simulation developed and used by CNES. It is based on a core software in charge of the real-time calculations of the simulation, and a patrimony that regroups all the different models developed on BASILES by other CNES users of the platform. It is today the most commonly used platform to create simulators at CNES, and so will be used for the MMX rover. Thus the familiarization with the BASILES platform is an important step of the job done during the internship.

2.3.3 Simulator architecture

The last step is to translate the simulation needs collected during the job interviews into a coherent simulator architecture. This architecture has to take into account every time, financial and fidelity constraints.

Chapter 3

Simulation needs

To identify the simulation needs, a first step is to sufficiently understand the MMX rover system. A context knowledge will have two intended effects:

- Ask relevant and comprehensible questions to the team members concerning the system. The answers to this questions will guide the conception of the simulator as it is a direct description of the simulation needs of the MMX team.

- Create a simulator architecture that will be faithful to the real system behavior and insures the minimum number of functions needed to qualify the system before the launch.

To understand exhaustively the rover two different studies will follow in this chapter.

First a system study which aims to explain the operation of the MMX rover.

Then a functional study that allows to look at the system in terms of functions and thus will be relevant for the design of the simulator.

Then a description of the interviews conducted with the MMX core team and their outcomes ends this chapter.

3.1 System engineering at CNES

The functional and system studies are a part of a general field of expertise called "system engineering". This subject can be ran in various ways depending on the company/agency considered. Thus before going on these two studies, this report will first describe how system engineering is used at CNES.

System engineering at CNES is a multidisciplinary project approach which aims to define, design, produce and validate complex systems (in the context of this internship: the MMX rover) according to the mission needs. This approach goes through different steps, from the system needs analysis to the system qualification.

This strategy follows a “V” shape cycle resumed in figure 3.1.

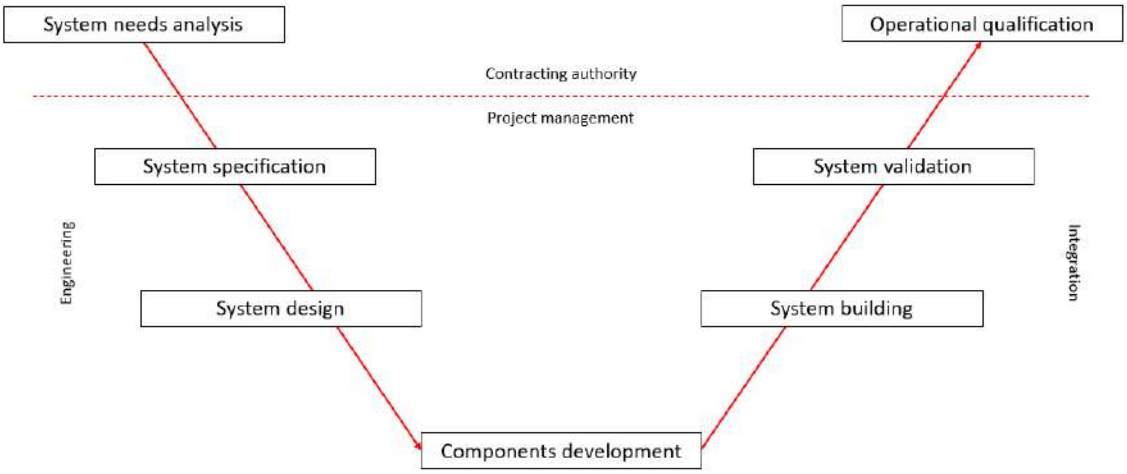

FIGURE 3.1: V development

In order to have a clear understanding of what this methodology consist of, the following part is a description of what are the objectives of each step.

- System needs analysis

  This section aims to list the general objectives of the project. It defines what are the points that need to be fulfilled in order to consider the project as a success.

- Systems specifications

  The system specification introduces the role of sub-systems to fulfill the needs identified in the previous step. It derives what the sub-systems are supposed to do in order to fulfill the system needs. For example one of the goals of the rover is to drive along a minimum distance of 100 m, thus the system needs to include a locomotion part that makes it possible for the rover to move.

- System design

  After the specifications of what the sub-systems have to do, the next step is to define how they do it in terms of performances and interactions between each other. So at the end of this step, all the technological solutions and their I/F are defined.

- Components development

  When the technological solutions are defined, the next step is to build them. This part is often delegated to other companies (in the particular case of CNES) that have the means to produce the sub-system products. Moreover some of these sub-system may need more time to be developed as they are state-of-the-art products.

- System building

  When all the sub-system products are developed and built, they are integrated together, either to form the final system, or grouped by sub-part because of testing needs considerations.

- System validation

  Once the sub-systems are grouped, the objective is to investigate their behaviour and insure that every sub-system reaches the minimum performances needed.

- Operational qualification

  After the verification at a sub-system scale, the whole system is tested. The testing conditions have to be as close as possible from the conditions that the system will meet during its mission.

It is important to note that this is a perfect representation of how projects are supposed to work at CNES. But it is not representative of how some projects work in reality. For the MMX project the simulation team is working by using specifications of the system even if the system specification step is not finished. So this “v” shape model is more of a guidance for project teams rather than a nominal procedure used every day at CNES. This is a quite common phenomenon as it is explained by the Mission Data Systems Division at the European Space Operations Centre:

> "The Spacecraft itself, its OBS and Spacecraft database are also under development at the same time as the Operational Spacecraft Simulator. [...] The likely changes that might occur in either of them will result in a respective change in the Simulator models or in a new integration of the most recent OBS and Spacecraft database. As a consequence, this requires a respective adaptation in the test and verification plan."[5]

Moreover, the software development has here an impact that needs to be specified. As mentioned in section 2.2, the first product delivered by the simulation department will test very simple mechanism within the system. This strategy has been implemented to match the development process of the flight software. Indeed, the flight software will at first be able to complete very simple tasks. Then along the project’s progress it will be enriched with new modules able to complete more difficult tasks. This development strategy is also the reason why the beginning of the simulator’s architecture is including a lot of hypothesis since some of the system specifications in terms of I/F are not yet available.

3.2 System study

The system study will go through the performances and I/F of each sub-system. This step is critical since no such document was available for the AVI/VS department, it was one of the main tasks of the internship.

3.2.1 Hardware

I. Solar array

The solar arrays are a critical part of the system. They are the only sub-system that provides energy to the rover. Thus their performances are one of the drivers of the system design. They provide power to the system during the day and will recharge the batteries so the rover can survive through the night.

> "The sun power at Mars is [...] around 30 to 50% of the power available at Earth. Phobos is submitted to a day-night cycle, each lasting three and a half hours, and the rover is unable to keep the sun normal to its solar arrays. These factors lead to a very limited amount of energy available each day. On the solar array, the simulations have shown an energy between 85 and 109 Wh per Phobos day, in worst and best case respectively."[2]

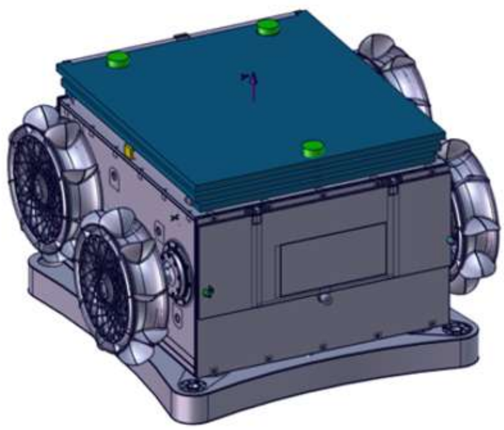

FIGURE 3.2: Rover in cruise configuration, clamped to the MMX S/C I/F platform

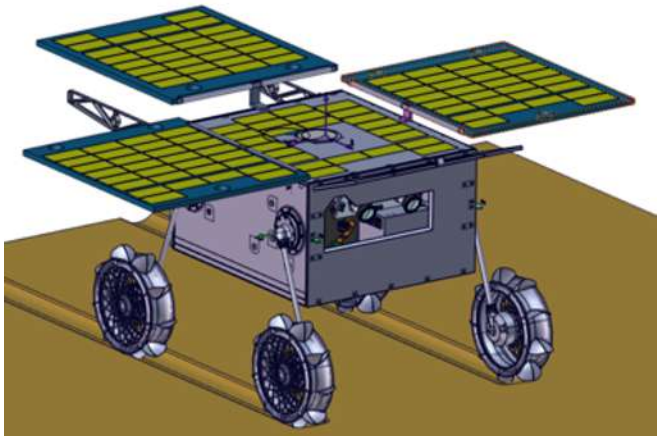

FIGURE 3.3: Roving simulation

The solar arrays are grouped when the rover is clamped to the MMX S/C as shown in figure 3.2. They are composed of one fixed panel and three others that can be deployed as it is shown in figure 3.3. Moreover it is important to take into consideration that once the solar arrays are deployed there is no mechanism on board able to regroup them as before, they stay deployed forever.

These power generation group will provide roughly (these numbers can still be changed since the power study is not finished) between 85 and 110 W depending on the solar arrays temperature and the solar flux.

The solar flux received depending on the inclination of the rover compared to the direction of the sun, it is possible to maximize the solar flux by changing the tilt of the solar arrays. This movement is done by changing the angle of the legs of the rover, and can change the tilt of the rover by approximately +/- 15 degrees.

II. Battery pack

In order to survive the night the rover will be equipped with a battery pack. This pack is composed of height batteries optimised for cold temperature and qualified for the Exomars mission. The battery pack capacity varies with its temperature between 130 Wh (cold case) and 165 Wh (hot case).

> "A large part of this energy is needed just to keep the inner temperature above the minimum allowed (0°C in order to preserve battery pack from early degradation). All the mission will be driven by the available energy. In the nominal case, it is foreseen to do something useful (drive, make science) each three Phobos days (so, each Earth day). The two others Phobos days, the rover will just restore the battery charge."[2]

Lastly, the battery pack is designed to last 300 charge/discharge cycles.

III. PCDU

As it stands for Power Control and Distribution Unit, the PCDU will manage the power on board. This sub-systems is able to provide energy to every other sub-system on board or not. It receives the sub-systems ignition and stop orders from the on-board computer. The PCDU is also able to monitor the currents and voltages used in the rover.

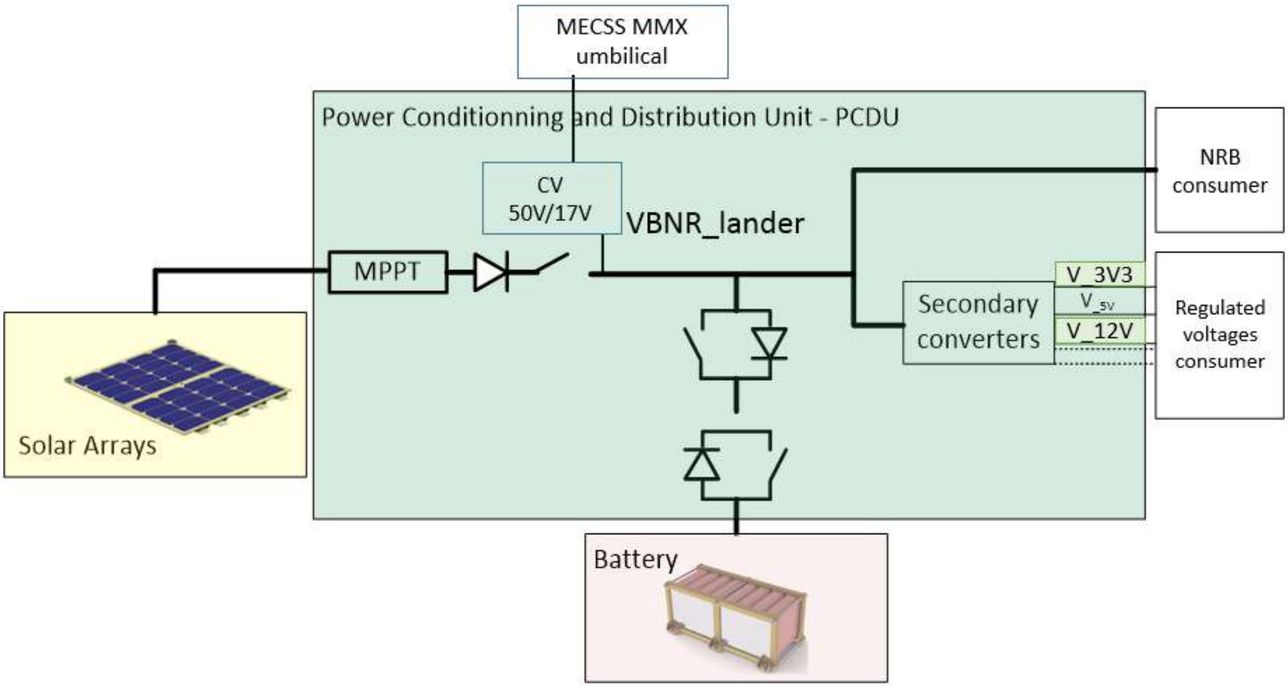

FIGURE 3.4: PCDU architecture

The ability of the PCDU to connect the S/C's power link (MECSS umbilical link) to the rover can be seen in figure 3.4. This will recharge the batteries during the cruise phase.

IV. Stereo bench

The first objective of the rover being to navigate a distance of 100 m, one of the needs is to know where are the obstacles along its trajectory in order to avoid any collision.

> "The Navigation Cameras (NavCam) are [...] often the driver in terms of design requirements. The reason for this is that they are used by Perception-Navigation-Path Planning chain which is in charge of ensuring a safe and efficient path for the Rover, [...] one of the most challenging requirements for the Rover." [6]

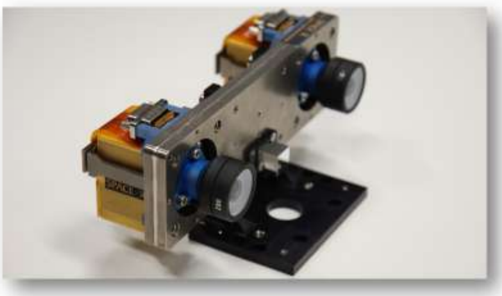

FIGURE 3.5: MMX rover stereo bench

The system needs to "look" at its environment. That function is insured by the stereo bench shown in figure 3.5, and can reach different levels of complexity.

- Ground assisted navigation

  In this case the rover starts by taking a picture of it's environment with the front camera. Then sends this picture to the ground segment. The operational team analyses the picture in order to observe any potential obstacle. After this analysis the ground segment sends a movement order consisting of a speed target, the duration of the movement and a direction. The rover accomplishes the movement and then the loop starts again.

  Here the rover is not autonomous for its movement since the decision from the ground is needed to continue the roving.

- Obstacle autonomous avoidance

  The rover is able to autonomously detect obstacles and derive their position from a set of picture took with the front camera. But it still doesn't have the ability to take the decision on which direction to aim for. Here the ground segment will simply send a target position without considering the threat of the presence of obstacles. Later, while accomplishing the movement order, the rover is able to avoid any collision on its own.

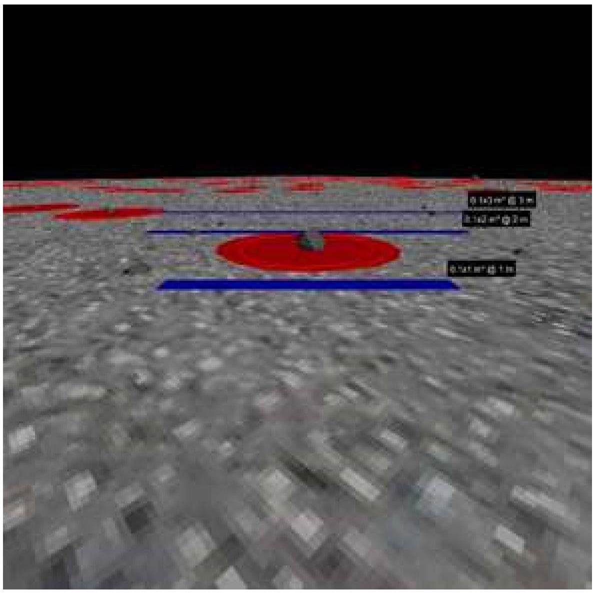

FIGURE 3.6: Example of the rover's perception of the environment

  In figure 3.6 the red zones are the avoidance zones where the rover understands that an obstacle is to be avoided.

  And if for any reason the rover is not able to go forward, it will simply stop and send a picture took with the front camera.

- Autonomous navigation

  This is the more complex case where the question "which is the best way to reach the navigation target?" is solved autonomously by the rover. To answer the question the rover first takes various shots of its environment in order to produce a complete panorama. By using this stereoscopic panorama the on-board software produces a "navigability map" like the one shown in figure 3.7.

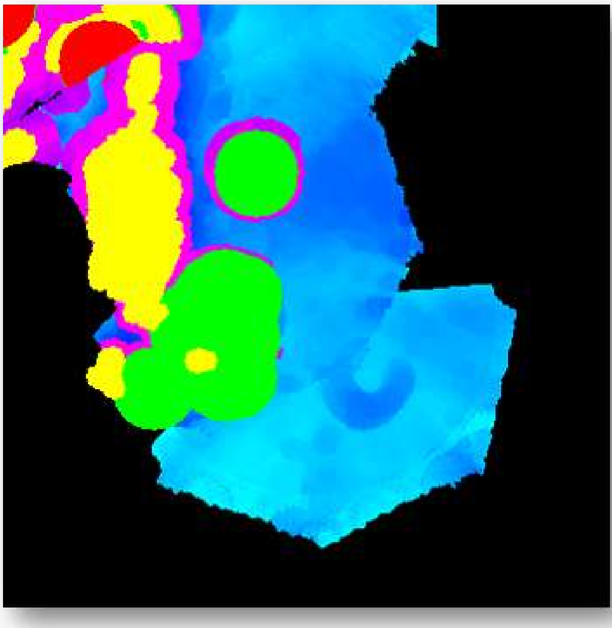

FIGURE 3.7: Navigability map, different colours reflect different risks level

By using this map the rover decides which way includes the least amount of risks. At the end of the procedure the rover knows what are the different movement options, knows which one is the best, and knows how this translates in locomotion orders.

In the case of the MMX rover project, a ground assisted navigation can't be considered for two main reasons:

- The S/C availability
  The MMX S/C will not be available all the time to insure the communication link between the rover and the ground segment (a more detailed explanation follows in the subsection V of the system study). Thus the operations team may not be able to communicate with the rover neither receive any data from it during a certain period of time,
- The communication viability
  The communication time delay with Phobos may vary between five and 25 minutes (depending on the relative position of Phobos and the Earth). That means that if the operational team programs a movement it will witness its consequences up to 25 minutes later. Thus even if the MMX S/C was all the time available to insure the communication link, it would still be impossible to "drive" the rover from the ground.

So the actual trade-off involves the two other solutions: obstacle autonomous avoidance and autonomous navigation.

CNES has a very strong expertise in the field of autonomous avoidance. The agency developed a specialised software called Environement de Développement pour la Robotique d'Exploration Spatiale (EDRES) that enables any rover to be autonomous in its movements aiming for a given target.

During this trade off, a consideration turned out to be essential: the performances of the autonomous navigation depends first and foremost on the quality of the environment perception.

The quality of this perception is usually controlled by three system specifications:

- The height of the camera taking photos to create the panorama

  A camera placed high up will allow to see a larger field, adding more information to the perception.

- The ability to turn the camera

  By taking pictures in several directions the panorama will include more information and thus improve the perception.

- The quality of the picture

  Obviously the quality of the perception depends on the quality of the picture took, more precisely on the number of pixel in one photo.

These abilities can be witnessed on the two rover of the missions *Exomars* and *Mars 2020* shown in figure 3.8 and 3.9.

FIGURE 3.8: Mars 2020 rover [7]

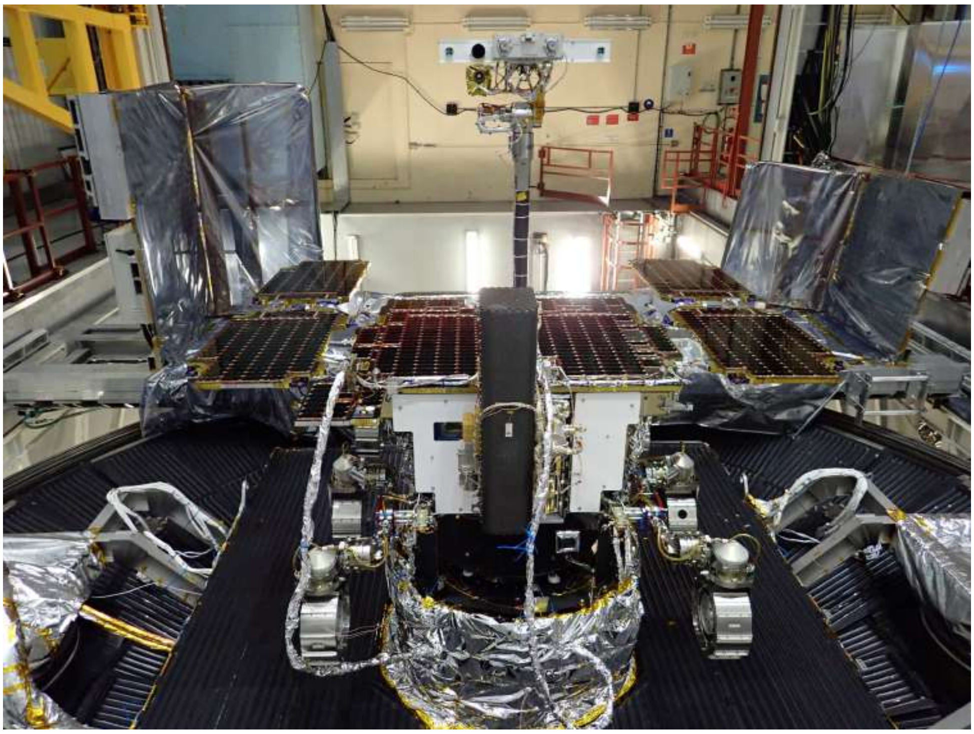

FIGURE 3.9: ExoMars rover [8]

The *Mars 2020* NavCam is located at a height of approximately two meters. The one of *ExoMars* is two and a half meters high. In addition to that, they are both able to rotate their NavCam

So for these two missions the panorama will be very large and thus the perception will be of sufficient quality.

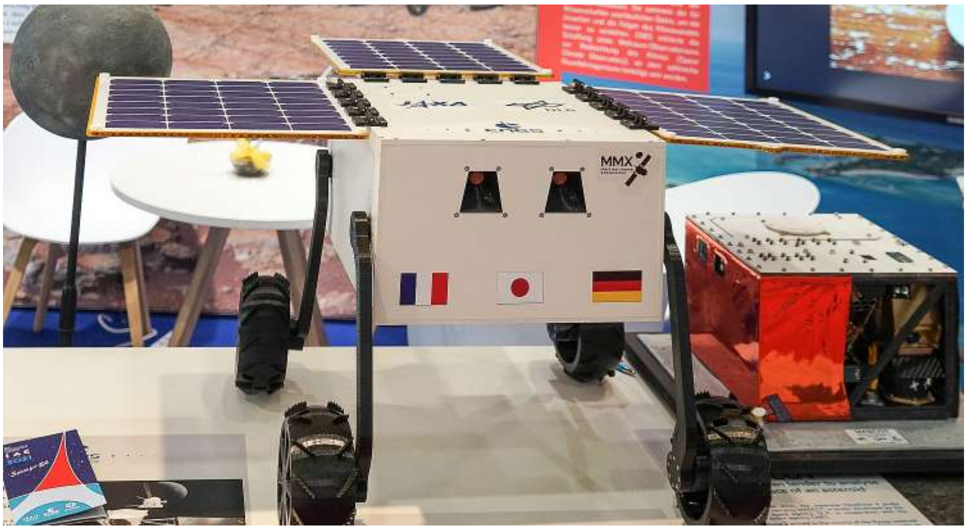

FIGURE 3.10: MMX rover
MMX rover

But in the case of the MMX rover the height of the camera is around 50 cm as it can be seen in figure 3.10. In addition, the NavCam is fixed with the frame of the rover. Thus if a panorama is needed, the whole rover will have to turn around itself in order to take shots in different directions. But the behaviour of the regolith being an unknown for now, the movement of "turning around itself" may lead the rover to "sink" in the regolith.

Due to the height of its camera and its lack in mobility the MMX rover is consequently not able to produce a perception of sufficiently good quality to ensure an autonomous navigation.

In conclusion, the rover will navigate on the surface with an "Obstacle autonomous avoidance" program. The ground segment will still play a major role since it is the responsible for the choice of the movement target.

V. Communication sub-system

A critical function of the system is to allow the exchange of information between the ground segment and the rover on Phobos. These exchanged information are called TeleCommand (TC) when they go from the ground to the rover. On the opposite direction (from the rover to the ground segment) they are called TeleMetry (TM).

The rover is equipped with an antenna and a communication management electronic card. The MMX S/C is also equipped with a communication box called RolBox (also developed by CNES). It is the MMX S/C that insures the link to Earth as the antenna of the rover is not powerful enough to send any data at an interplanetary range.

The communication links used during the mission are described in figure 3.11.

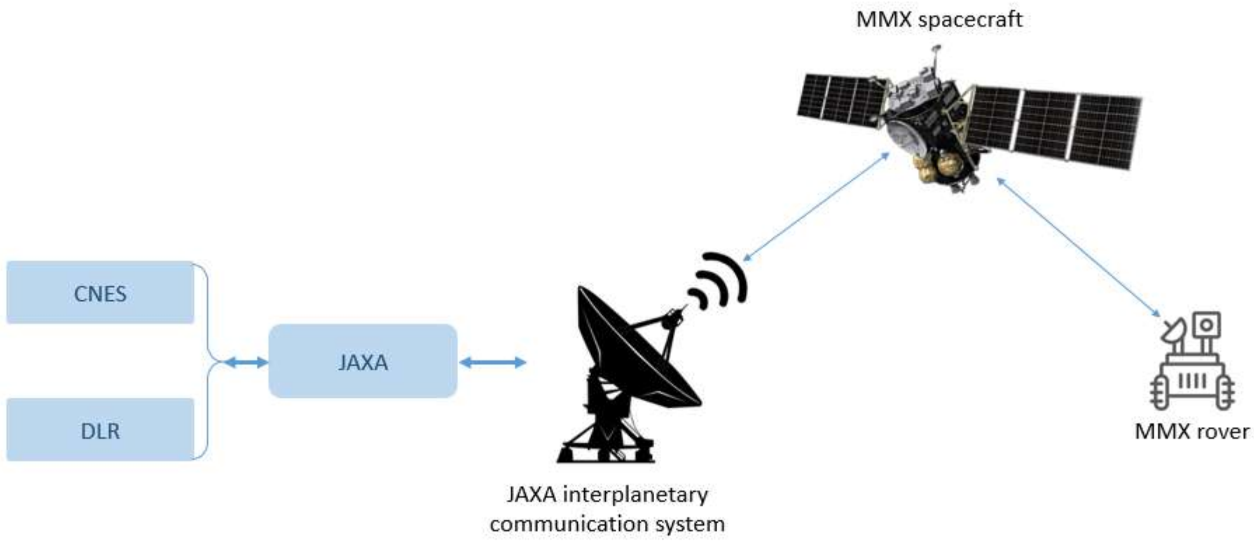

FIGURE 3.11: Communication links

Moreover the communication sub-system needs to take into account the position and the aiming of the different entities involved. Indeed, the MMX S/C design doesn't allow it to communicate with the rover and Earth at the same time. Thus there will never have a direct communication link between the rover and Earth during the whole mission. Note also that any communication link established between the rover and the S/C will last maximum 20 minutes. The S/C is in orbit around Phobos and will not stay overhead the rover.

The communication plan spans three phobosian days (one Earth day):

- 1st day: S/C/Earth link

  Rover data transferred towards the ground segment and ground instructions transferred to the S/C,

- 2nd day: S/C/rover link (maximum duration of 20 minutes)

  Ground instructions transferred to the rover and reception of the rover's data,

- 3rd day: S/C/rover link (maximum duration of 20 minutes)

  Ground instructions transferred if the previous communication slot was not sufficient and reception of the rover's data.

It is also important to note that the communication link used between the S/C and the Earth doesn't ensure the same performances as the one used between the rover and the S/C. In fact, the telemetry link with Earth is weaker than the telemetry link with the rover. Therefore a part of the telemetry from the rover will be stored in a mass memory on-board the S/C. These data will be sent to Earth later on when the S/C will be orbiting Mars.

The S-band equipment and the rover as the RolBox and the S/C are connected via an UART link.

VI. Locomotion wheel and joint

To accomplish the objective of rolling 100 m on the surface of Phobos the rover is equipped with four wheels driven by electric motors. These four wheels are linked to the main frame with tilting legs also driven by electric motors. Wheels and legs together form the "Locomotion group" (shown in figure 3.12) and insure the mobility of the rover.

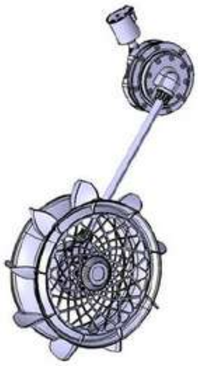

FIGURE 3.12: Locomotion group

"The drive train is designed to fulfill three purposes:

- Execute the self-righting moves required to bring the rover in an upward position after landing,
- Drive the rover to a location on the surface of Phobos,
- Orient the body of the rover in order to maximize the performance of the science instruments and to maximize the energy flux on the panels."[2]

The importance of the electric motors driving the legs of the rover during the up-righting phase is highlighted in figure 3.13.

FIGURE 3.13: Uprighting sequence

Rolling under micro-gravity is a constrain that strongly affects the locomotion group. The system's behaviour and dynamic are not completely mastered. The gravity of Phobos is approximately 0.0057 m/s^2 which is very small compare to 9.80665 m/s^2 on Earth. Thus, inertia phenomena may be less predictable than on Earth.

Moreover the behavior of the regolith is also an unknown affecting the locomotion group. The data on the surface of Phobos are insufficient to understand precisely how the regolith will behave.

> "The composition of Phobos regolith is still not constrained unambiguously. [...]. Mechanical properties of the surface soil, [...] are among the most essential parameters for designing a lander/sampler [...]. However, mechanical properties of Phobos regolith are poorly constrained due mostly to the difficulty in estimating the particle sizes, particle size-distributions, the packing density of the regolith and other frictional parameters."[9]

Lastly, the locomotion group is not designed neither qualified by CNES. It is a subsystem under the responsibility of DLR.

A more detailed description of how the electric motors are wired in the system, and what kind of signals they exchange with the rest of the system can be found in the appendix A.

VII. Locomotion box

The locomotion box is in charge of the eight electric motors control. It traduces the locomotion order form the OBC in an understandable control law by the eight electric motors.

The locomotion box works with a set of sensors that measure the turning speed of the wheel and the legs angular position to produce the control law of the electrical motors.

This equipment is designed and qualified by DLR.

VIII. Attitude sensor box

The main objective of this sub-system is to measure the attitude of the rover at any time. To insure this service it is equipped with two kinds of instruments: gyroscopes and accelerometer which can be seen in figure 3.14.

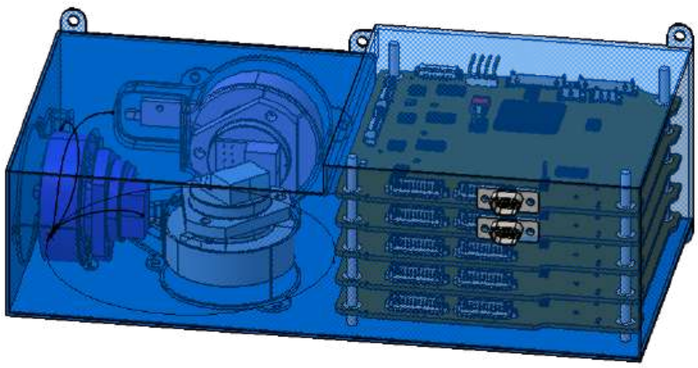

FIGURE 3.14: Attitude sensor box

Moreover the accelerometer can measure the gravity acceleration vector of the Phobosian gravitational field. This could help to set the origin of the attitude integration if for any reason the set given by the MMX S/C is lost.

IX. Mechanical, Electrical Communication and Separation Subsystem

Throughout the commissioning phase the rover will be connected to the MMX S/C via a specific platform. It allows to communicate with the rover, provides heat to the rover and vibrations protection. It allows to produce and send to the ground health checks of the rover by using the antenna of the MMX S/C.

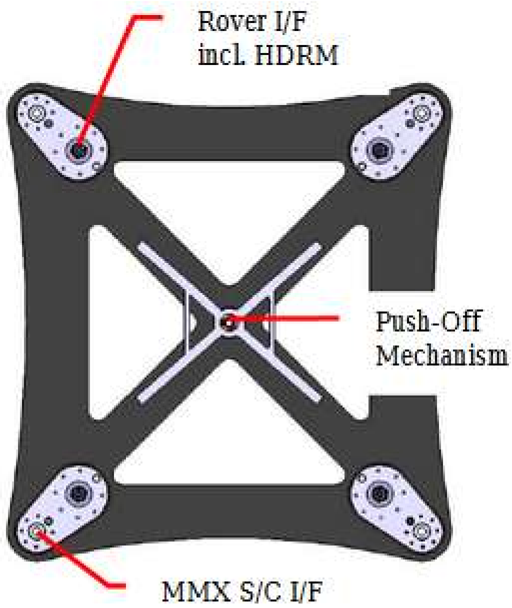

FIGURE 3.15: MECSS

During the launch the MECSS together with the dampers will ensure that the rover can withstand the accelerations forces. The results of a vibration study on the frame of the rover (to simulate the launch) can be found in the appendix B. Lastly, the MECSS will insure the separation of the rover from the MMX S/C. To do so, hold mechanisms are retracted and a spring between the rover and the S/C is released. This will push the rover off the MECSS platform and place it on its falling trajectory toward Phobos. A more detailed figure of how the MECSS is connected to the MMX rover can be found in appendix D. The MECSS along with the ejection mechanisms can be seen in figure 3.15.

X. Wheel Camera

There are two wheel cameras on the rover. They are orientated in order to watch the front and the rear left wheels. The pictures taken by these cameras will help to better understand the regolith behavior at the surface of Phobos. The objective is to observe the regolith flux around the wheel. By comparing the real footage and models simulation it will be possible to adjust the models to match the reality. The results may improve our understanding of the regolith's properties like cohesion and viscosity. These two cameras are under CNES's responsibility.

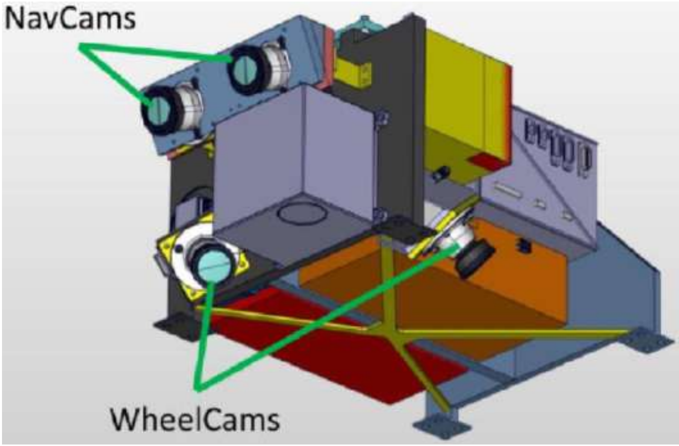

FIGURE 3.16: Wheel cameras & NavCam [3]

"There will be two identical WheelCams on the rover. These panchromatic cameras have a 2048 x 2048 pixel resolution and a spatial resolution of approximately 35µm at the center of the image. [...] Colored LEDs lighting the scene will allow multi spectral imaging at night."[2]

The report "A rover for the JAXA MMX mission to Phobos" describes the scientific objectives of the WheelCams as follow:

> "The WheelCAMs will be used to image the wheels and their interaction with the regolith. By observing the properties of the regolith compaction and flow around the wheels it will be possible to characterise the mechanical properties of the regolith itself. In addition, the WheelCAMs spatial resolution will be sufficient to characterise the size distribution of regolith particles and their angularity."[2]

The wheel caeras along with the navigation cameras are shown in figure 3.16.

XI. MiniRad Experiment

The report "A rover for the JAXA MMX mission to Phobos" describes the scientific objectives of MiniRad as follow:

> "The miniRAD instrument wil investigate the surface temperature and surface thermo-physical properties of Phobos by measuring the radiative flux emitted in the thermal infrared wavelength range. [...]The instrument will thus directly address or contribute to addressing fundamental MMX science objectives and provide a basic picture of surface processes on airless small body. Furthermore, miniRAD will help to characterize the space environment and the surface features of Phobos, thus enabling a comparison with asteroids."[2]

This experiment is based on the MARA experiment on board the Mobile Asteroid surface SCOut (MASCOT) project. It is a radio spectrometer able to study the surface of Phobos at a decimeter scale. Its overall design is shown in figure 3.17.

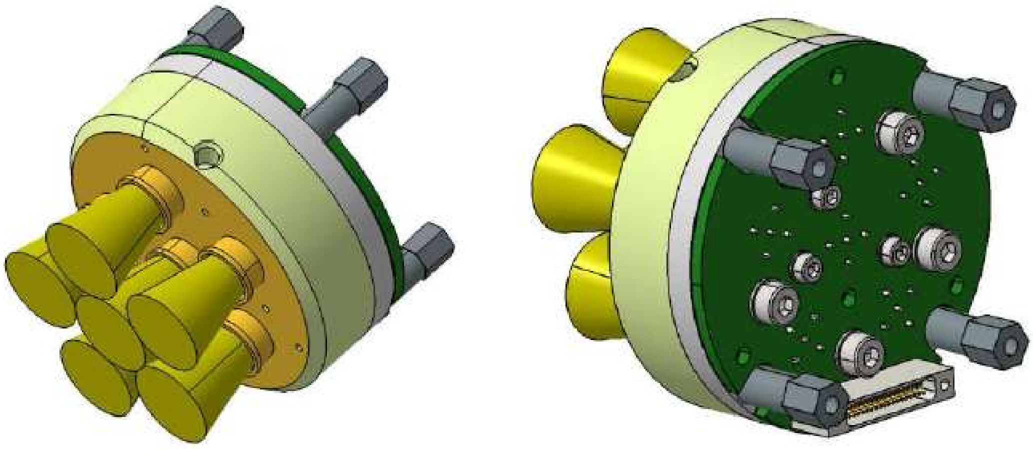

FIGURE 3.17: Preliminary design of MiniRad experiment

Thanks to the rover mobility this experiment studies the geological heterogeneity of the ground by visiting various sites.

During the cruise phase, MiniRad will have to calibrate its measurements by focusing its instruments on a target purposely placed in the frame of the rover.

XII. RAX Experiment

> "RAX [...] will perform Raman spectroscopic measurements to identify the mineralogy of the Phobos surface. The RAX data will support the characterization of a potential landing site for the MMX S/C and the selection of samples for their return to Earth. The RAX measurements will be compared with Raman measurements obtained from the RLS instrument during the ExoMars 2020 mission, to provide evidence for the Martian or non-Martian origin of the surface minerals of Phobos."[2]

Based on the spectrometer on board Exomars, the RAX module studies the mineralogical composition of the surface of Phobos, its preliminary design can be seen in figure 3.18. By working between 530nm and 700nm it will be able to determinate the nature of any mineralogical, organic or aqueous compound.

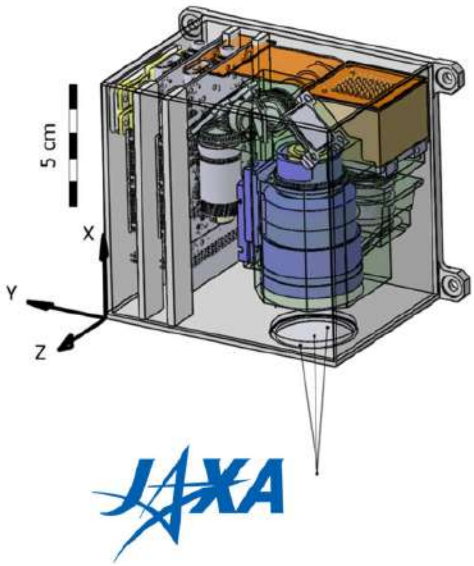

FIGURE 3.18: Preliminary design of the RAX module

This equipment is under DLR's responsibility. The agency will have access to the results of MMX rover but also to the ones of Exomars, therefore it will allow a comparison between both instruments and may help to understand the origin of Phobos. Our current knowledge leads towards three hypothetical scenarios.

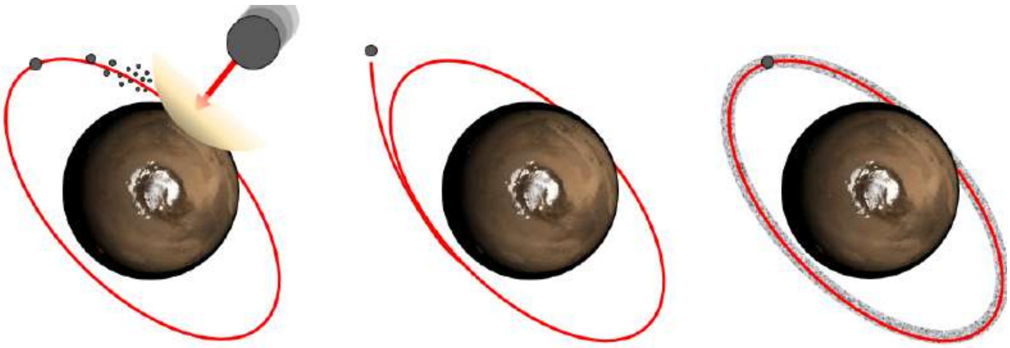

FIGURE 3.19: Phobos formation hypotheses

Phobos may be: the result of a collision between Mars and another body, a stranger body captured by the gravity of Mars, the result of the gravitational reformation of a dust cloud in Mars's orbit. These hypothesis are graphically explained in figure 3.19.

XIII. OBC

The On Board Computer is "the [...] unit where the OBS run"[10]. The OBS needs to communicate with all the sub-systems of the rover and exchange different kinds of information with several communication protocols. To accomplish these tasks, the OBC is usually composed of several elements:

- DC/DC converter and switching module,
- Telecommand, Telemetry and On Board Time module,

- Reconfiguration and Local Mass memory module,
- Processor Module,
- One or more I/O modules to connect to either standard or non standard interfaces,
- One back-plane to connect the modules together.

More information and details on the different parts within the OBC can be found in appendix G.

The specifications of the OBC also include two more information: the communications links it will handle and the signals it will have to supply and process.

The OBC has to supply the following communication links:

- six SpaceWire (SpW) links:
  - two links dedicated to WheelCams,
  - two links dedicated to NavCams,
  - one link dedicated for the locomotion sub-system,
  - one link for the RAX module
- 5 Transmitter (Tx)/Receiver (Rx) RS422 links:
  - one link for the MiniRad module,
  - one link for the attitude sensor,
  - one link dedicated to the communication card,
  - one link for the MMX S/C.

More detailed information about these two kinds of link can be found at [11](SpW) and [12](RS422).

Lastly the OBC has to provide and process the following signals:

- four Pulse Per Second (PPS) signals for the cameras,
- Analogical signals:
  - 30 I/F for temperature sensors used for the thermal control of the rover,
  - 13 I/F for temperature sensors used by the Hold Down and Release Mechanism (HDRM),
  - three I/F for Shape Memory Alloy (SMA) mechanisms,
  - four I/F for temperature sensors used during the pre-heating of the electric engines of the locomotion group VI,
  - two I/F for temperature sensors used during the pre-heating of the electric engines of the "flappers",
  - seven I/F containing five signals coming from the sun attitude sensor,
- Discrete signals:
  - two signals for the separation sensors of the MECSS,
  - four signals for the separation sensors of the shutters,
- On/Off command signals:
  - two signals for the Navcam's LEDs,
  - height signals for the Wheelcam's LEDs.

3.2.2 Software

I. Flight Software

The OBS ensures:

- Communication with the MMX S/C,
- rover management (power chain, thermal chain,...),
- attitude control,
- equipment management,
- instruments management,
- data management for files in memory.

> "The “On Board Software”[...] is known as the software implementing [...] vital functions such as: attitude [...] control in both nominal and non-nominal cases, telecommands execution or dispatching, housekeeping telemetry gathering and formatting, on board time synchronisation and distribution, failure detection, isolation and recovery, etc."[10]

The previous quote from ESA highlights the fact that a majority of OBS share common functions.

Since these functions are frequent, the space industry tries to produce reusable parts of the flight software for time and cost reduction purpose. That led to a generic OBS architectures composed of "building blocks" that can be used for different missions (also called "partitions" of the OBS).[13].

CNES has initiated studies concerning this standardization of the OBS and came up with its own OBS generic platform called LVCUGEN.

This generic platform "aims at providing to the space community, and maintaining an off-the-shelf framework, based upon a set of generic software building blocks, a qualified development process and associated offline tools." [14]

It is based on a Basic software that contains [14]:

- An Xtratum hypervisor that manages the memory and time segregation between the different partitions. Xtratum [...] allows, among others, the partitions to communicate through RAM ports with each other,
- I/O drivers libraries that offer standardized interfaces that can be used by the partitions that need to access directly to I/O devices,
- A partition Mode Management and Data Load (MMDL) that manages the software modes, software patches, software configuration control, and memory dumps at computer level,
- A partition Hardware and Software Events Monitoring (HSEM) that manages the payload computer Failure Detection Isolation and Recovery (FDIR) inside the computer,
- A partition "IOServer" that manages the shared I/O inside the computer.

LVCUGEN is already operated on-board the Angels and Eyesat nanosat missions.

Its structure is resumed in figure 3.20.

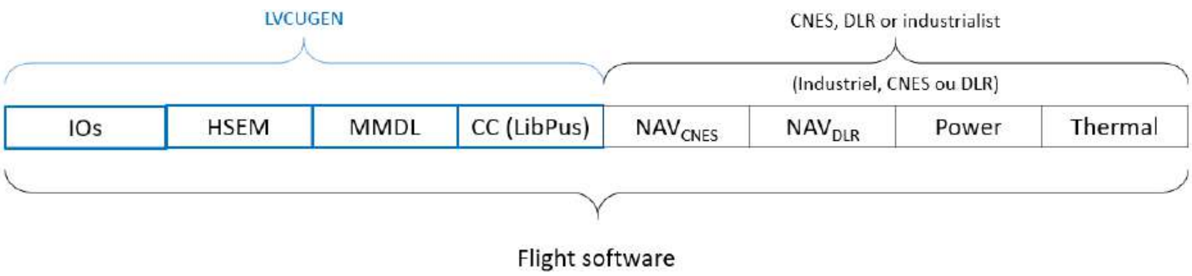

FIGURE 3.20: LVCUGEN Structure

A more detailed explanation of how it works and additional information on this topic can be found in appendix C.

3.3 Functions study

The functional study breaks down the different functions that the rover has to carry out to fulfill its mission. The final simulator's architecture will be based on these functions thus ensuring that the behavior of the simulator will be sufficiently close to the rover's one. I identified these rover's functions in two different descriptions of the system:

I. Rover modes

A mode of the rover is defined by:

- functions to be fulfilled by the rover,
- autonomy level to be reached,
- equipment and/or instruments that can be turned On/Off,
- an optional change in the rover configuration (for example electrical or thermal).

It describes the capabilities of the rover depending on its activity. In other terms the functions the rover has during the different phases of the mission. A complete explanation of these modes can be found in appendix E.

II. System study

The system study carried out in section 3.2 is also a good indicator of what are the functions of the system. Both hardware and software descriptions highlight the functions of each sub-system which leads to the general goals of the rover.

In both cases I used two different functional analysis tools.

- Functional chains,
- Energy and information chains.

These tools adopt different points of view on the system.

The functional chains aim to understand the sequence of actions that leads the rover to solve a task. Whereas the energy and information chains describes what are the main actors in transmitting energy or information within the rover.

Both of these tools help to understand the behaviour of the rover and play an important role in the identification of the needed function within the simulation environment.

I. Functional chains

The power chain describes the actions taken by the rover to manage the energy on-board during different phases. It is represented as follow:

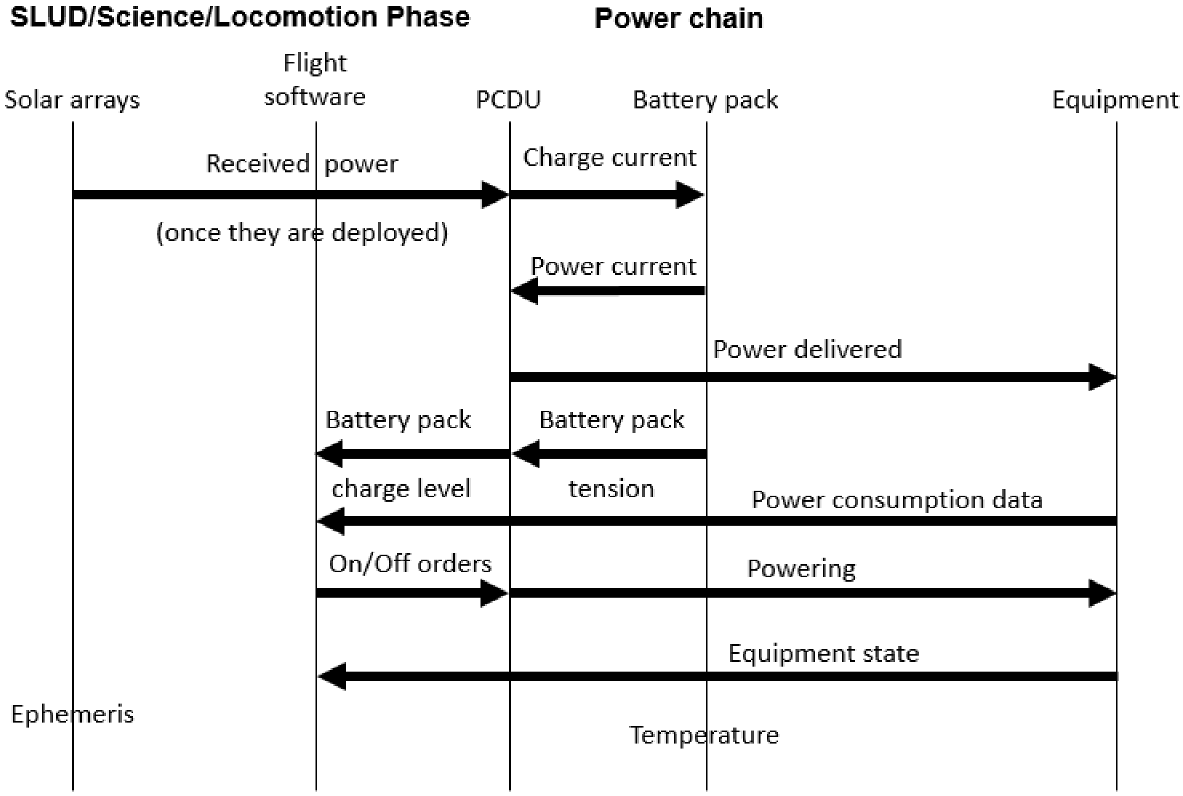

FIGURE 3.21: Power management chain

Every vertical line represent one sub-system within the rover. At the bottom of these lines one may find elements that have an impact on the behaviour of the sub-system. The horizontal arrows represent the signal/information exchanged between two sub-systems.

In each chain one can identify sub-systems that exchange a lot/often information. These sub-systems may be grouped together in order to simplify the structure of the simulator.

In figure 3.21 the PCDU and the battery pack are together involved in 80% of the exchanges. This criteria may later on lead to the regrouping of these two models in the simulation environment.

The other functional chains produced can be found on the appendix F.

By reproducing the same reasoning for the other chains I ended up with a first clue of what could be the different groups used within the simulation environment.

In order to take into account other consideration I used another functional analysis tool.

II. Energy and information chains

This tool focuses on the sub-systems that create a movement within a system. Thus in the case of the rover this concerns the locomotion part. Energy and information chains help to understand how a movement is processed and executed by a system, there structure is shown in figure 3.22.

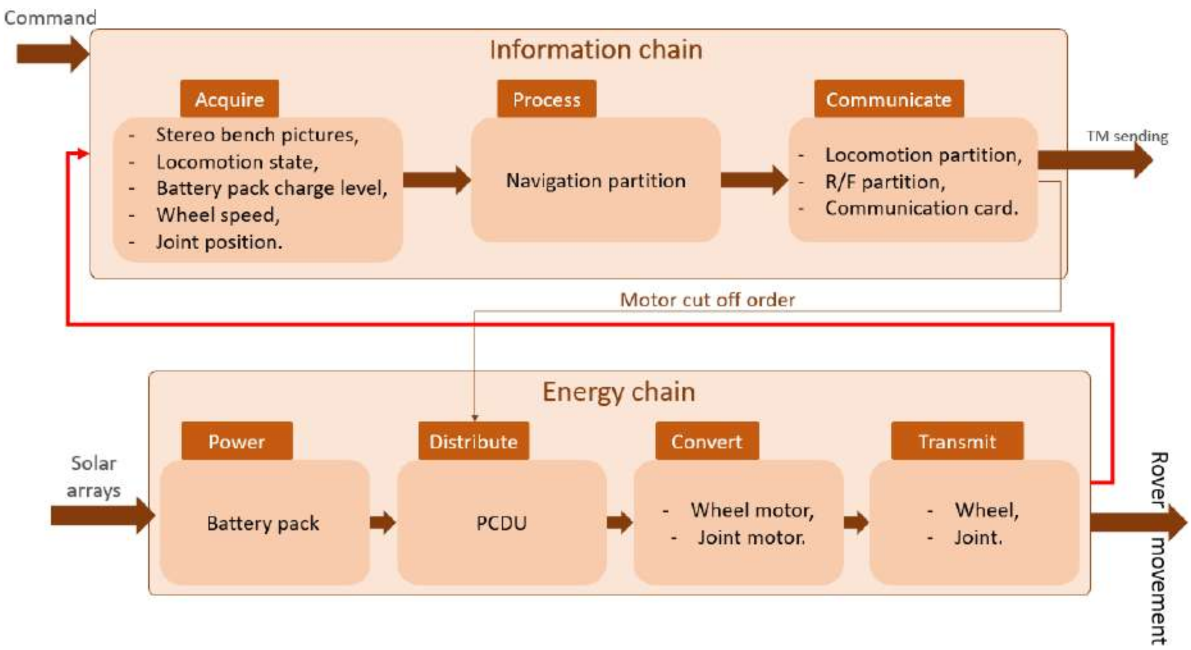

FIGURE 3.22: Locomotion energy/information chains

This tool proposes another point of view. In this one the battery pack and the PCDU are no longer grouped. Whereas some sensors of the system are grouped together to acquire the information needed for the locomotion.

These two tools help to identify the most important parts of the system. If a group of sub-systems insures the same functions then this could be considered during the simulator design.

But theoretical tools are not the only way to understand what are the needs for the simulator. The other way is to ask directly to the people who will work with the simulator.

3.4 Identified needs

The system study and the functional study specified the technological and functional background of the rover. This was essential to come up with relevant questions to the MMX core team, thus deriving an efficient architecture for the simulator. The main factors that have an influence on the design of the simulator are summed up in figure 3.23.

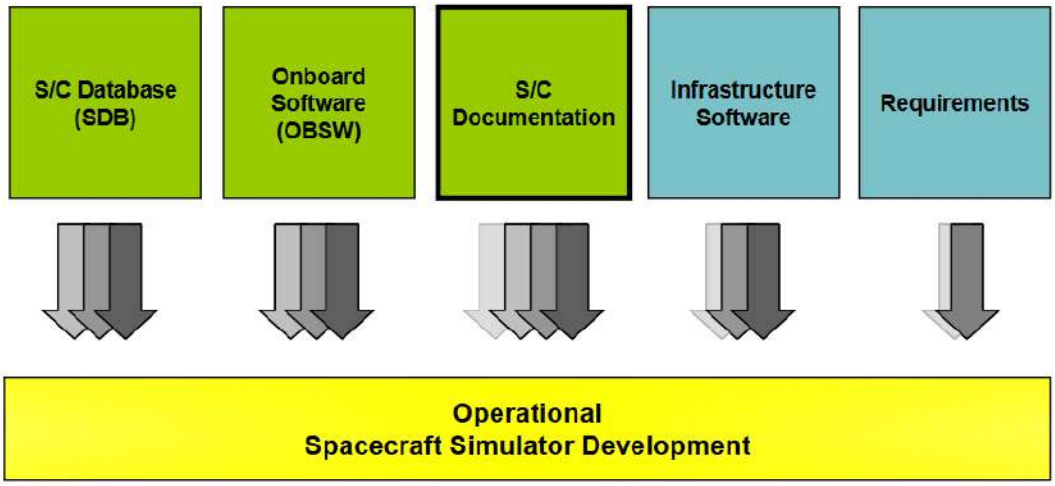

FIGURE 3.23: Simulator design considerations

The design of this simulator answers to different kinds of needs.

The first kind encountered in the process is the validation need. It is usually expressed by the members of the team asking for the conception of the simulator. Validation needs corresponds to data/variables that will be monitored during the validation and/or the qualification process. They regroup the minimum set of variables/functions that need to achieve a defined level of performance to consider the system as ready to go.

Next comes the simulation need. It is the translation of the validation need in the simulation environment. Unlike the validation need which constrains the system, the simulation need constrains the simulation environment. This constrain depends in majority on the fidelity required. While a simple actuator may contain only one information (On/Off, not deployed/deployed, clamped/released, etc...) more complex sub-system may use very complex functions. The fidelity with which these functions are represented in the simulator is a major question.

A low fidelity level is a concern for the viability of the simulator, but a high fidelity level is synonym of a higher cost and a longer time to produce the simulator.

Therefore a "good" design for the simulator ensures that every validation need is well represented by a simulation need in the simulation environment.

The first essential step to a "good" design is to collect the needs of the MMX core team. To do so I carried out several meetings involving one or more people from the project. These meetings were guided by several questions:

- What is the scope of your activities?
- What are the sub-systems involved in your daily work?
- What are your most important validation needs?
- Do you already know any existing simulation technologies that could satisfy your validation needs?
- What are the means interacting with these technologies?

- What fidelity level can be considered as acceptable concerning your validation needs? (What elements needs to be simulated? If they are simulated, how well do they represent the reality?)

The complete form used during the interview can be found in the appendix H. Seven interviews were conducted with persons from the MMX core team:

- Flight software (Elise Aitier and Gabriel Brusq),
- Avionics (Julia Le Maitre and David Granena),
- Robotics and uprighting (Jean Bertrand),
- Regolith and science (Simon Tardivel),
- Mechanisms, flight dynamics and attitude sensors (Frans Ijpelaan),
- Operations (Cedric Delmas),
- Communication (Céline Loisel).

The following part describes the outcomes of these interviews. It highlights the main considerations of the MMX core team regarding the performances needed in the simulation environment.

I. Flight software

The OBS is implemented on the OBC, thus the performances of the OBS depend directly on the performances of the hardware involved in the OBC. This has an impact on the design of the simulator. The simulation environment may be hybrid (involving hardware and software support) or all-digital.

The OBC hardware can be connected to a computer running the simulation environment. It is the more realistic situation where the calculations of the OBS are done by the real OBC. But it implies that every entity of the project using the simulation environment needs another OBC. A new OBC costs approximately 15000 euros while an "OBC like" can decrease this value to 1000 euros. So a hybrid solution comes with higher fidelity but will be reproduced at a higher cost.

The OBC can also be emulated on a computer. In order to do this all hardware elements have to be converted into numerical models. An emulated processor adds the ability to skip the simulation duration. Indeed if the processor involved in the simulation is a digital model, its calculation process can be accelerated. This allows to pass long periods of time in the simulation where the rover is only charging its battery for example. Moreover the simulation environment can be easily shared since no hardware part is involved. But the actual state of the art of digital models is not able to emulated a processor as fast as the Arm 9. Thus this solution will not be used for now.

Another consideration concerns the interfaces used in the simulator. Interfaces are in charge of the communication of information between two sub-systems of the rover, they use communication protocol to translate the same information in two different technological environments. Since the testing phase aims to monitor the behavior of the OBS, the interfaces between the OBC and the rest of the rover has to be exactly the same as the ones used in the rover. It stabilizes the results of the simulation and decreases the risk of errors.

This interview highlighted two main validation needs:

- The simulation environment must be shared easily at a reduced cost,
- The interfaces used in the simulator have to be true to reality.

These validation needs can be translated in simulation needs:

- The simulation will run on a hybrid environment,
- The interfaces models used between the OBC and the simulator have to use the actual communication protocols used within the rover.

II. Avionics

The avionic team is responsible for the electronic devices on board the rover. For example they manage the different power links within the system.

This department confirmed the need for a true to reality fidelity from the interfaces between the OBC and the rest of the system.

They produced a very important document called the "avionics architecture". It sums up all the power/data links within the system. A reproduction of this document can be found in appendix I.

Moreover, during the testing of the flight software, the teams need to observe the behavior of data communication. This means to be able to "look" inside the communication protocol models and verify that the process is not changing the nature of the information.

This meeting led to new validation needs:

- The simulation environment must handle these communication protocol models: RS422, RS485 and SpaceWire,
- These communication models must allow the introspection of the communication.

That can be translated into simulation needs:

- The simulator has to include three different models for three different communication protocols,
- The simulation environment has to monitor the communication process. Some parameters in the communication protocol models must allow the introspection of the information.

III. Robotics and uprighting

The robotic team works on the different movements of the rover and the management of its power. It is this team that was involved in the choice of the navigation strategy. At the time of this meeting this strategy was not yet set.

As the locomotion is one of the main topic of this team the first validation need expressed concerns the dynamic behavior of the rover on the simulated ground of Phobos. The quality of the simulated motion depends on the fidelity of the dynamic model. This is still one of the major concern for the team since the behavior on Phobos is not very well known. But as mentioned in the system study 3.2 CNES has developed a platform called EDRES purposely built to test navigation programs. For time and money consideration it was decided to look for an interfacing between the simulation environment of the rover and the EDRES platform. This could allow the simulation team to use the EDRES program in the BASILES platform of the simulator.

This department is also responsible for the uprighting procedure. This part of the project also brought new needs. To test the viability of the uprighting procedures the team needs to play different falling scenarios. In fact the position of the rover at the beginning of this procedure depends on the flight dynamic of the rover during the fall on Phobos. Thus the robotic team needs to select different beginning situations at will in a limited time.

The robotic team expressed two new validation needs:

- The simulation environment could use the dynamic model used in the EDRES platform,
- The changing from one falling case to another must be easy and not time consuming.

Translated into simulation needs:

- The interfacing of EDRES with BASILES may be done in two different ways. A co-simulation environment can be considered (using the outputs of EDRES as inputs for BASILES). Or the use of a part of the computation code can also be a solution,
- The simulation environment must embed a selection of different starting positions for the uprighting procedure.

IV. Regolith and science

This team manages science data coming from the experimental devices. They also provide models that may be used in the simulator:

- Phobos shape model
  This model consists of multiple triangular facets. These facets represent the surface of Phobos with a precision going from 2 m^2 to 150-200 m^2
- Phobos ground model
  This model generates a random shape to represent the ground of Phobos. It can also generate geological formations, rocks and obstacles at the surface. This model doesn't use any real data on Phobos ground. The team is trying to improve this model by using real picture of Phobos ground.
- Gravity model
  A simple equation gives the gravitational field generated by a body of any shape. Thus applied to Phobos this model can provide a sufficiently good approximation of the value of gravity at any point on the surface of Phobos.
- Ephemeris model
  This model also is the application of one equation. This equation gives the position in orbital parameters (Inclination, longitude of the ascending node and argument of periapsis). It will be used to give the position different objects in Phobos sky: MMX S/C, the Sun and Mars.
- Regolith model
  As mentioned before the mission aims to improve our knowledge of phobosian regolith. Thus the available models are not sufficiently precise to

be representative of the regolith behavior. But some considerations may guide parameters of the simulation. For example by using data on the sphericity of regolith grains and their Hamaker constant, the science team makes the hypothesis that the burial of the rover will not exceed two to three centimeters.

– Ground contact model

The DLR has developed a ground contact model in order to design the locomotion sub-system. But the core team at CNES doesn't have any information on this model.

The CNES experimental modules i.e. the Wheel Cams will use compression algorithm to share/store pictures. This compression algorithm has an impact on the pictures quality and therefore on their scientific value. Beside these compression algorithm, other programs aim to correct image defects. The science team needs to test these algorithms and insures that the final quality will be sufficient to exploit the pictures.

The scientific team provided important models for the simulator but has also validation needs:

- It must be easy to test and change pictures related algorithms,
- The representation of gravity field and geometrical shape of Phobos are considered as perfect (their fidelity is considered as negligible when compared to other models used in the simulator).

With this associated simulation needs:

- The simulation environment has to monitor the different algorithms used to modify the picture of the Wheel Cams,
- The different models provided by the science department will be added to the models used in the simulator.

V. Mechanisms, flight dynamics and attitude sensors

This department manages the attitude measurement of the rover. This measurement involves hardware and software. The list of hardware instruments used is not yet finished. The rover will be equipped with gyroscopes in order to compute its attitude and a sun sensor to derive its position with respect to the Sun. More detailed information on these instruments can be found in the appendix J. During the navigation sequence the tilt of the rover will not change a lot. Thus the measurement of its attitude doesn't have to be very precise. The objective is to measure this attitude with a ten degrees accuracy in less than 100 seconds.

But the team is also looking to add an accelerometer to the rover. This instrument could add new capabilities such as the measurement of the local gravity vector. One of its appealing outcomes concerns the attitude initialization.

The gyroscopes need an initial attitude in order to compute the attitude changing and give at any time the current attitude of the rover. This origin is given by the MMX spacecraft after the separation. But if for any reason the rover looses this initial attitude reference the computation of the attitude can be lost. The accelerometer can provide a new initial attitude by measuring the local gravity vector with respect to the rover attitude once on the surface of Phobos.

Finally, the attitude measurement department is equipped with instrument validation facilities. Thus the instruments will not be tested on the simulator. However the information provided by the gyroscopes are needed as input for other models in the simulator and therefore a gyroscope model is necessary within the simulator.

Validation needs:

- The simulator must provide an attitude data flow. These data must provide the same behavior as the real gyroscope with a ten degrees accuracy and a 100 seconds computation time.
- The presence of an accelerometer in the rover is not excluded. Its functional role may turn out to be crucial for the mission. However it is not yet confirmed so the simulator must be able to operate without taking into account the accelerometer.

Simulation needs:

- A gyroscope model will be embedded in the simulator. The outputs of this model will provide dynamic values of the rover's attitude. These values have to be coherent with the current attitude of the rover in the simulator.
- An accelerometer model can be considered depending on the changing in the project. This model could provide different values of the gravity vector (direction and intensity). This vector has to be coherent with the current position of the rover in the simulator.

VI. Operations

The operations groups every interaction between the ground segment and the rover during its mission. They will provide the TC and receive the TM. Thus the most critical part in this department is the way we send any information to the rover. The communication protocols used by the operation team are tested and validated by their own means.

Validation needs:

- The communication protocols to send TC to the rover and receive its TM must be exactly the same as the ones used in reality during the mission.

Simulation needs:

- The interface of the simulator must provide a choice of different protocols to communicate with the rover within the simulation environment.

VII. Communication

This team insures the quality of the communication link between the rover and the control center. Therefore it concerns the communication electronic card, the antennas, and the modulator. As for the operations team the communication protocols must be the exact same ones in the simulator as the ones used within the rover. Moreover the procedure to start a S/C / rover communication involves functional conditions. For example to initiate a communication the S/C will first send a "hello" message looking for an answer. If the S/C antenna is in the visibility field of the rover's one then the communication is received. The rover confirms the reception by sending an answer, then the communication may start.

The communication hardware may also be connected to the simulator to be qualified.

Validation needs:

- The communication protocols must be true to reality. The communication functional procedures must also be represented (initialization message, reception, confirmation, communication start).
- The validation of the communication hardware may also be conducted through the simulation environment.

Simulation needs:

- The communication protocols and functional procedures must be embedded into the simulator,
- The track of a connection between the communication hardware and the simulation environment will be considered during the design of the simulator.

Chapter 4

BASILES platform

The second main objective of the internship was to get acquainted with the simulation platform: BASILES.

It is a numerical real-time simulation platform designed by CNES and developed by the company Spacebel. Capable of creating and operating complex simulators, it is not specific to space application and can be used whenever there is a need to simulate a complex system.
The rover simulator will be design on BASILES. Therefore a training period on this platform was needed to understand how it affects the architecture of a simulator.

The training period was divided into three different phases:

- BASILES introduction traineeship at Spacebel headquarters (half a day) to understand the structure of the software,
- Creation of several simple simulator highlighting BASILES capabilities,
- Creation of a very simple simulator meant to represent the power management within the rover.

4.1 BASILES structure

The BASILES platform is divided in two major parts.

The first one is the calculation core and is usually not used during the design and the operating of a simulator. Its purpose is only to compute every operation needed during the simulation.
The second part is where the design and the operating of the simulator take place. For simplification the name BASILES refers to this part in the following development.
Any simulator designed on BASILES uses a hierarchical structure composed of four different elements:

- The simulator itself,
- Scenarios,
- Models & entities,
- Variants,

The following part defines the role of these elements by taking the example of a very simple simulator: an electrical circuit with a resistance and a generator schematized in figure 4.1.

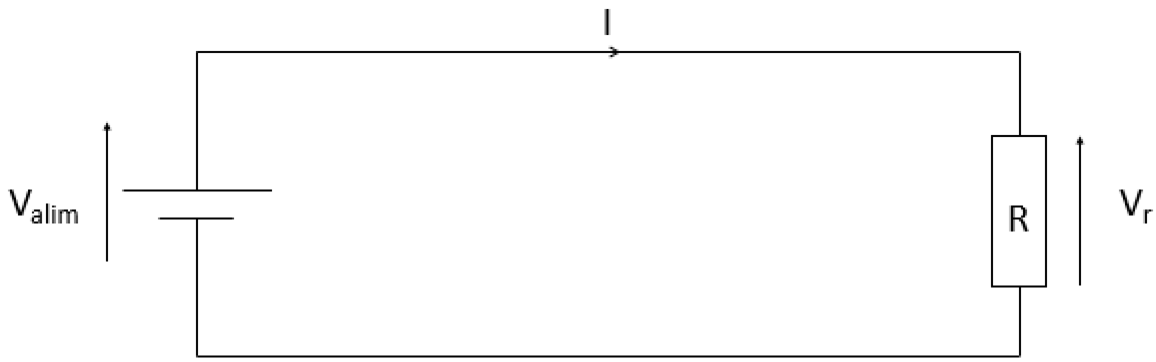

FIGURE 4.1: Electrical circuit

The objective is to choose the power supply tension V_{alim} and the resistance impedance R to compute the intensity I through the circuit.

I. Models & entities

Models are the most important part of the simulator. In the current example two models have to be created : a generator and a resistance. They consist of a group of functions, parameters, with a programmable behavior. In this example:

- The generator has one parameter: its tension.
- The resistance has
  - One parameter: its impedance,
  - One internal variable V_r,
  - One output: the intensity I,
  - One behavior equation which is the Ohm law: I = V_{alim}/R.

Entities are versions of the same model with different parameters set. In the current example a first entity of the resistance model can have a 5 Ω impedance while another one sets 10 Ω. But in both cases the entities come from the same model. Moreover a simulator can embed several entities of the same model.

II. Variant

A variant is a version of the simulation environment that includes entities and their interactions (the connections between their different inputs and outputs).

III. Scenarios

Once the models are created the next step is to configure the simulation environment. This means to set:

- The duration of the simulation,
- The different means of introspection,

In this example the needed interface link is: V_{alim}=V_r which comes from Kirchhoff's second law. And the only introspection concerns the intensity of the circuit which is an output of the resistance model.

A setting of this kind is called a scenario. Scenarios use the same models but different variants, interfaces, introspection means.

The structure of any simulator based on BASILES can therefore be summed up in figure 4.2.

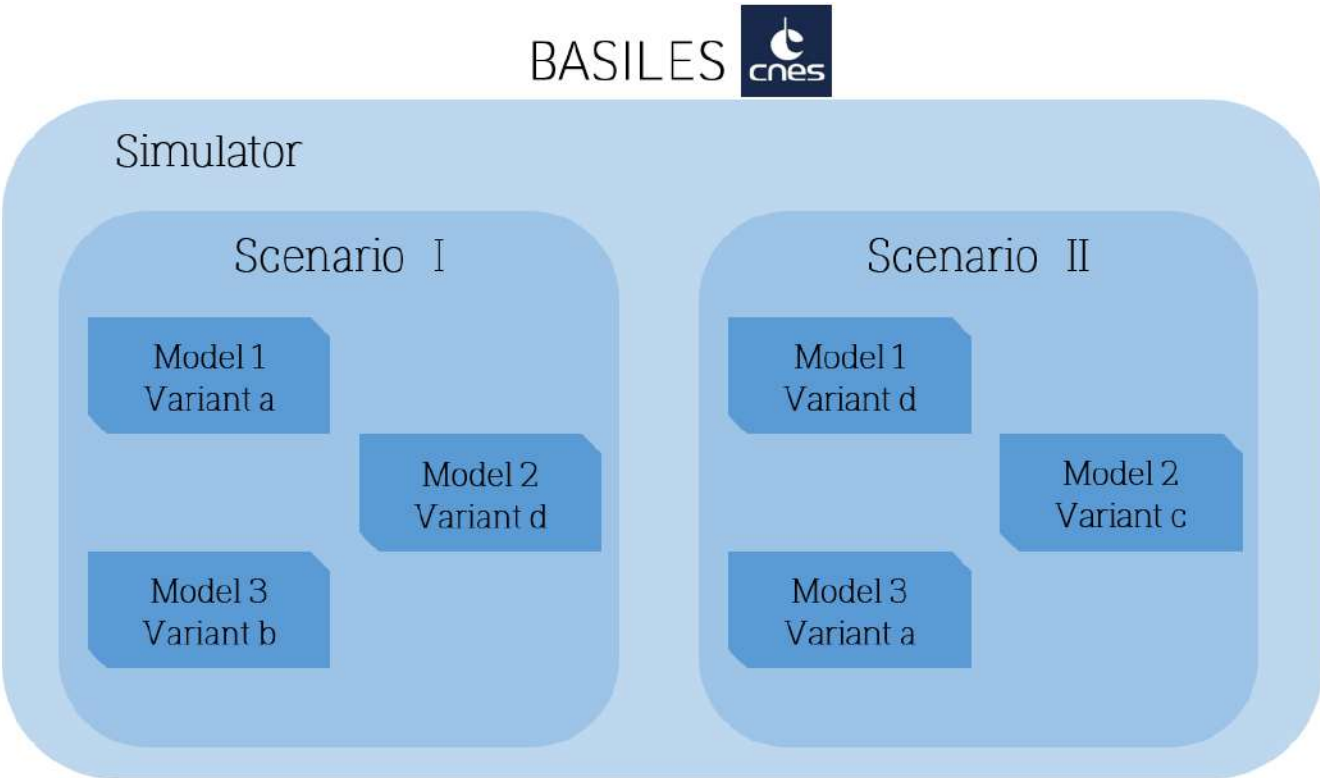

FIGURE 4.2: Simulator structure

When it comes to the conception of real simulators used at CNES the tasks are divided between the agency and private companies. CNES designs the simulator architecture and writes the simulation needs. Then private companies provide the different models associated to the hardware used.

But in the case of the rover no equipment is produced by a private company, thus no model is delivered to CNES. All the models used in the rover simulator will be either produced by CNES or will be ordered to private companies.

4.2 Development training simulators

These training simulators are of various difficulties and help to understand the main functionalities of the BASILES platform. After the simple resistance circuit other electrical simulators were made:

- Resistance & capacitor (shown in figure 4.3

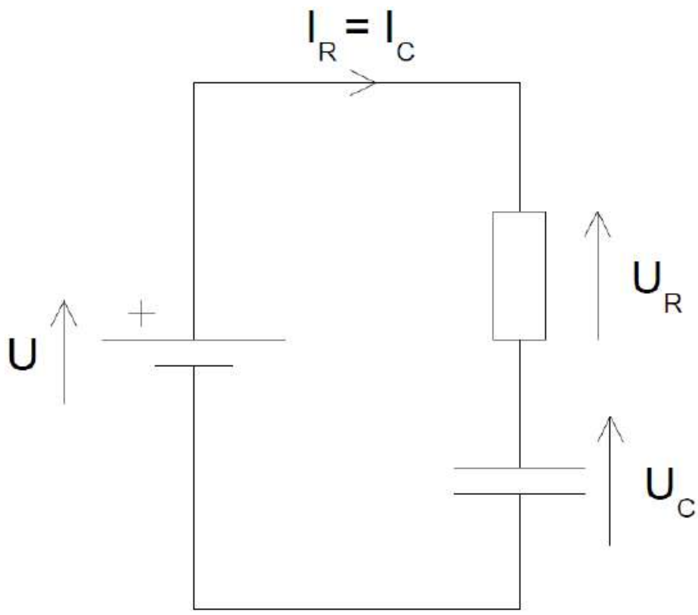

FIGURE 4.3: RC circuit

The equations that describes this circuit are the following:

$$\begin{cases} I_R = I_C \\ U = U_R + U_C \\ U_R = R * I_R \\ I_C = C\dfrac{dU_C}{dt} \end{cases} \Rightarrow \begin{cases} I_R = I_C \\ U_R = U - U_C \\ I_R = \dfrac{U_R}{R} \\ \dfrac{dU_C}{dt} = \dfrac{I_C}{C} \end{cases}$$

FIGURE 4.4: RC circuit equations

These equations being differential, this simulator introduced differential computing on BASILES.

The platform uses a Runge Kutta 4th order to integrate any variable if needed.

Unlike the simple resistance circuit which provided constant outputs, the resistance & capacitor introduced dynamic computation. The simulator needs now a computation loop that can be summed up in the figure 4.7:

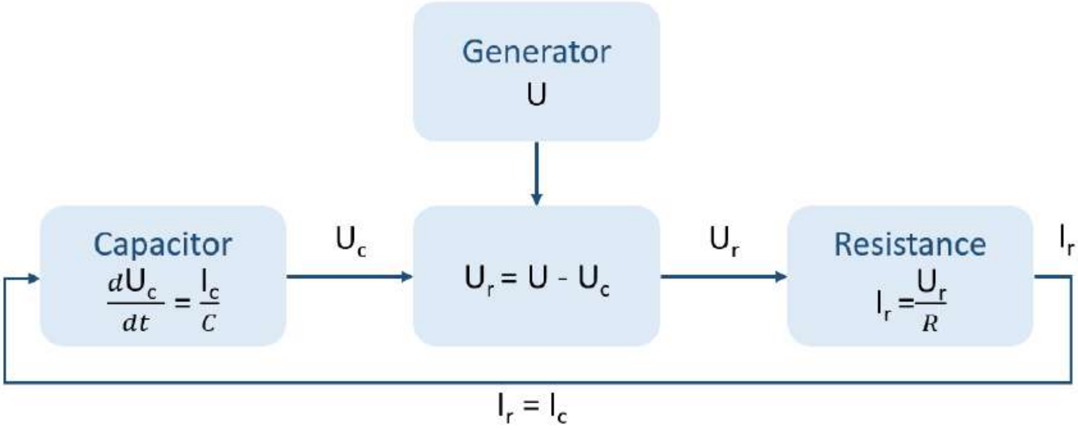

FIGURE 4.5: RC circuit computation loop

The results of this simulation can be found in figure 4.7 and 4.7.

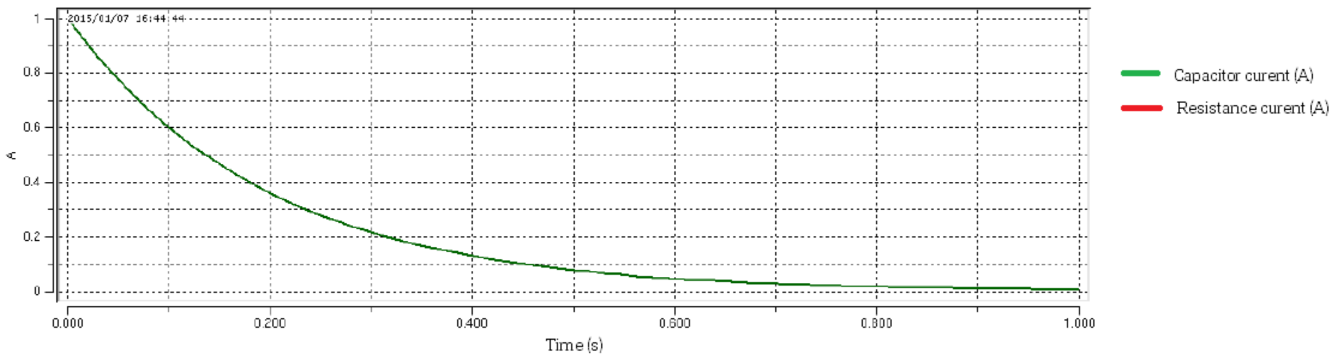

FIGURE 4.6: RC circuit intensities monitoring

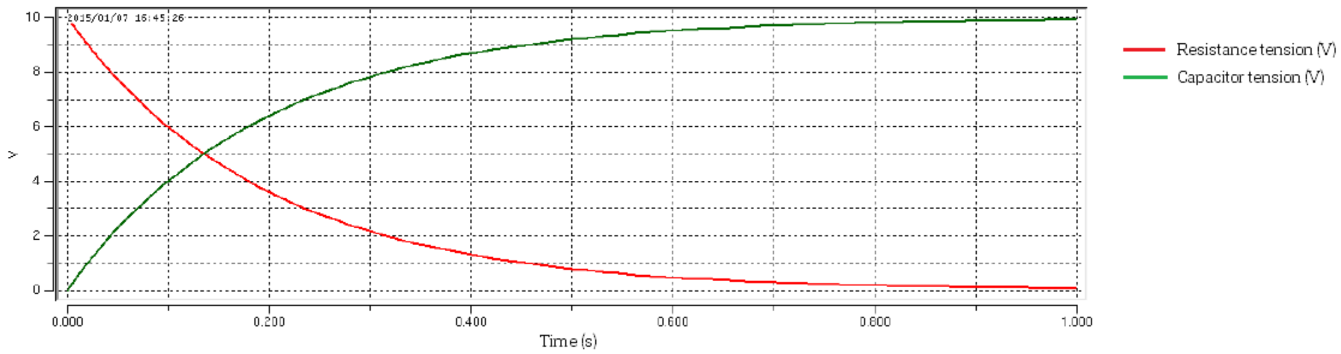

FIGURE 4.7: RC circuit voltages monitoring

A similar simulation was made with a Resistance, capacitor & inductor circuit and also led to correct results.

- Resistance & capacitor with switches

  This simulator introduced new capacities of the platform: conditioned model behavior changing. Its structure is shown in figure 4.9.

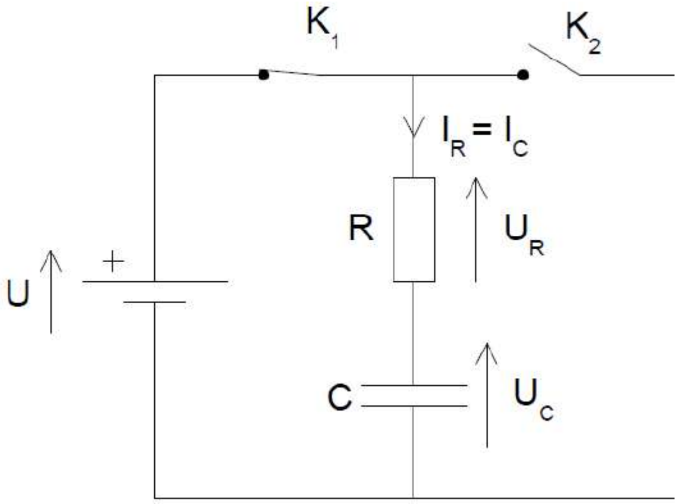

FIGURE 4.8: RC circuit with switches

The expected behavior is the following:

I. The K1 switch starts closed and the K2 open, the generator starts to charge the capacitor in the left loop,
II. Once the capacitor is charged, Uc = U, the K1 switch opens itself and the K2 closes itself and the capacitor discharges in the right loop,
III. Once the capacitor discharged the cycle starts again.

Therefore a new model was created for the switches. This model needs to detect the moment when the switch changes its state. This capability comes from two kinds of parametrization in the BASILES platform: "activation & activation point". In this example the "activation point" reads the value of the capacitor tension. When this value is equal to U, the activation point triggers the activation. This activation then commands the changing of the state of the switches.

The same kind of behavior can be found in the rover. For example if the battery level gets too low a TM message should be sent to the ground segment to warn the operation team. In this case the activation point is the battery level and the activation is the sending of a TM.

4.3 Simplified rover simulator

Following this training I decided to design a simplified version of the rover on the BASILES platform. The objective is to simulated the power management on board the rover.

This simulator embeds several models:

- Battery

  The battery model is composed of one parameter to monitor its charge level, and another parameter to monitor its connection state with the solar array.

- Solar flux

  Different versions of this model were created. A first one providing a constant flux value. A second one providing a sinusoidal value. And a last one able to read an external Excel document containing values coming from a Phobosian sunshine model.

- Solar array

  This model converts the solar flux received in power generated. It can be affected by several parameters: the solar array area, the efficiency of the panels and a coefficient which represents the state of cleanliness of the panel.

- Gyroscope

  A gyroscope model was added only to simulated equipment power consumption. Therefore this model uses only one parameter: a configurable power consumption level. It can also provide its On/Off state.

- PCDU

  The PCDU model was designed to monitor the On/Off state of the other equipments. It also computes the energy sent to the battery after taking into account the power consumption of all the on-bard equipments.

The architecture of this simulator is shown in figure 4.9.

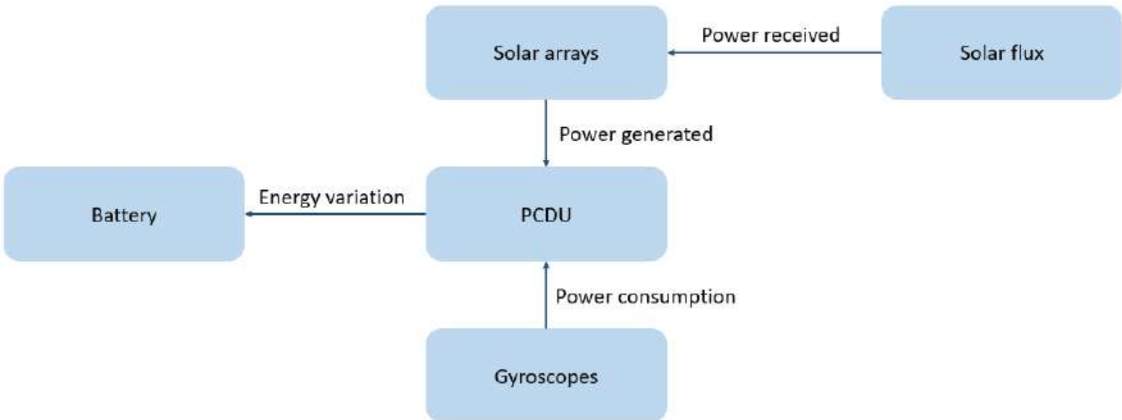

FIGURE 4.9: RC circuit with switches

The connection between the models and the information they share is not part of the model design. It is done during the scenario design. Through this step it is also possible to set the computation parameters (calculation step, integrator type, introspection signs, etc...). Once designed this simulator can show the ability of the rover to survive depending on the sunshine conditions. It is an example of how a simulator can help during the design of a complex system.

Chapter 5

Simulator architecture

The outcome of the two previous chapters are now used to design the architecture of the Training Operations and Maintenance Simulator (TOMS):

- The function and system studies gave indications on the expected behavior of each sub-system and how to regroup them by function. Taking into account the validation needs coming from several interviews this gives the content of the architecture,
- The training on BASILES gives the framing of this content. It provided insights on how the function groups must behave together inside the BASILES platform.

The function groups identified are the following:

- Power management,
- Communication,
- Science,
- Maneuver management,
- Environment,
- Thermal control,
- Mechanism management.

This chapter aims to derive the general architecture of the simulator that will be developed for the rover. The content and the behavior of every model used in the simulator is subject to change since the system itself is still in design phase. But I designed the architecture in order to allow any modification of the models (as long as it doesn't affect the functions of the rover).

This architecture is defined function by function in the following sections.

5.1 Power management

The power management function regroups three different models:

I. PCDU

   - Provides the state (ON/OFF) of every sub-system,

- Turns on or off every non "one-use" sub-system,
- Monitors the different voltages and intensities used in the system and derives their energy consumption,
- Derives the total energy consumption
- Derives the total dissipation energy,
- Communicates with the OBC to transmit the energy management data.

Note: If the PCDU shows that an equipment is turned off, this equipment shall not be able to send any answer to any request from any other equipment within the system.

II. Battery

- Monitors the battery energy level,
- The capacity is impacted by the ambient temperature provided by the environment model. This influence is modeled according to a linear assumption summed up in figure 5.1.

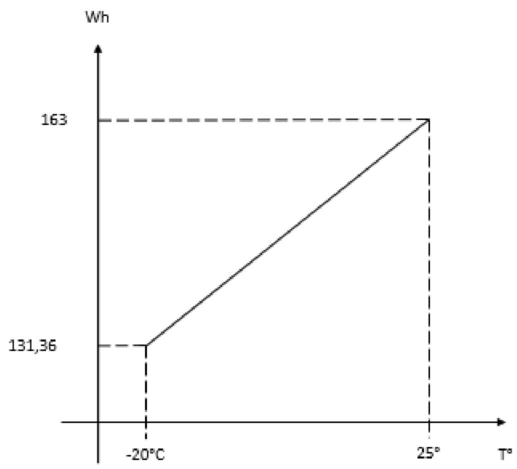

FIGURE 5.1: Linear assumption for battery capacity over temperature variation

This assumption, like other following ones, simplifies the development of the model and can be completed in the future.

- Takes into account the charging duration.

III. Solar array

- Provides the generated power according to the sunshine model coming from the environment group,
- The power generated depends on the inclination of the sun direction with respect to the solar arrays plan. This influence is modeled according to a sinusoidal assumption depicted in figure 5.2.

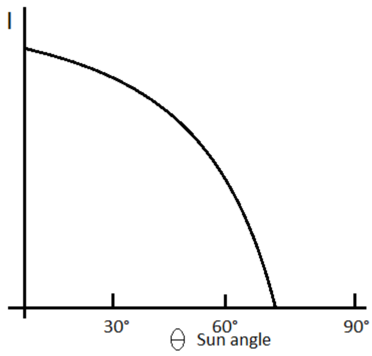

FIGURE 5.2: Power generation (proportional to current intensity) over inclination change

- Takes into account an efficiency coefficient and a cleanliness coefficient.

The architecture of the power management model is represented in figure 5.3.

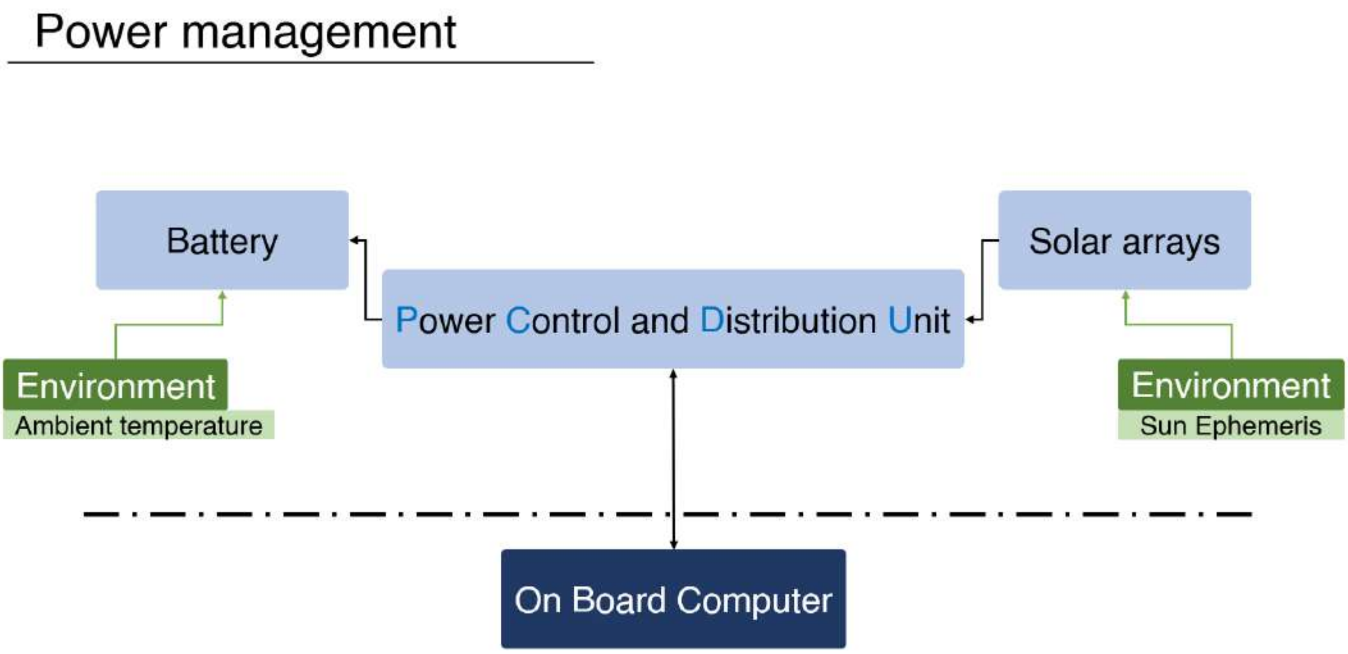

FIGURE 5.3: Power management model architecture

5.2 Communication

The communication group involves the Radio Frequency (RF) card, the rover antenna, S/C antenna and the rolbox.

I. RF card

- Transmits any TM generated by the OBC using the related communication protocol,
- The uplink data rate is 32 kbps,
- Decrypts TC sent by the ground segment using the related protocol,
- The downlink data rate can be configured between 32 and 512 kbps,

II. Rover antenna

- Monitors the communication gain depending on the inclination of the rover, the ephemeris of the MMX S/C and the attitude of the MMX S/C. The MMX S/C may be above the rover but turned towards the Earth. In this configuration no communication is possible between the rover and the S/C.

  The gain of the communication link varies along the angle between the axis of both antennas. This angle varies with the position of the MMX S/C. The real gain variation is represented by the blue region in figure 5.4:

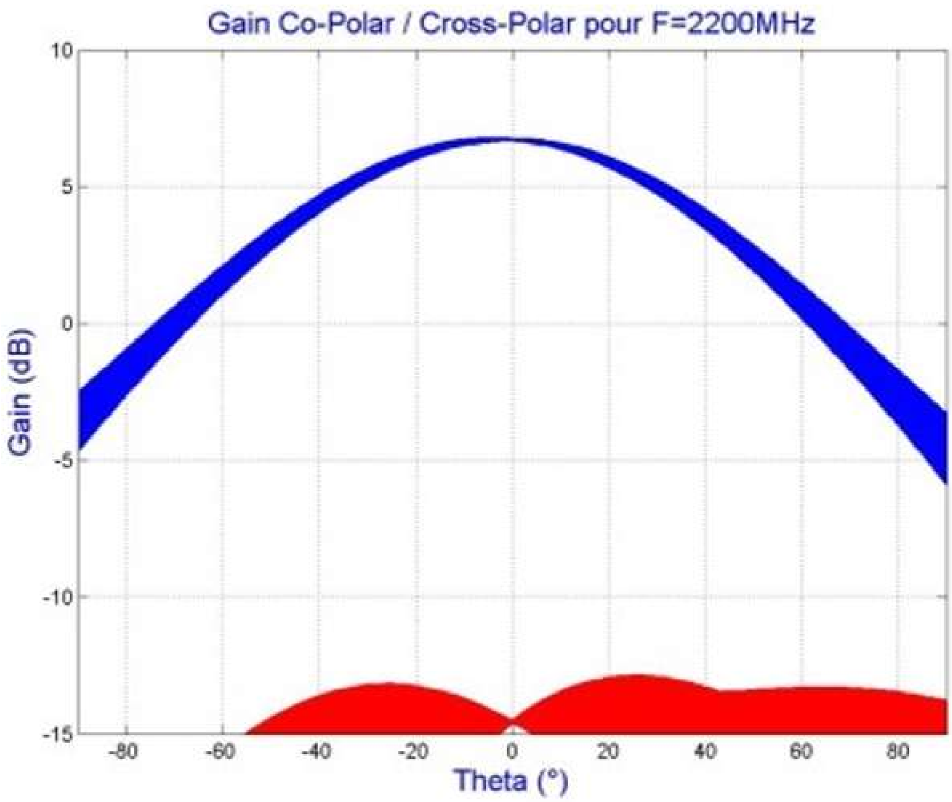

FIGURE 5.4: Communication gain profile

  The behavior of the gain over this angle is assumed to follow the curve shown in figure 5.5:

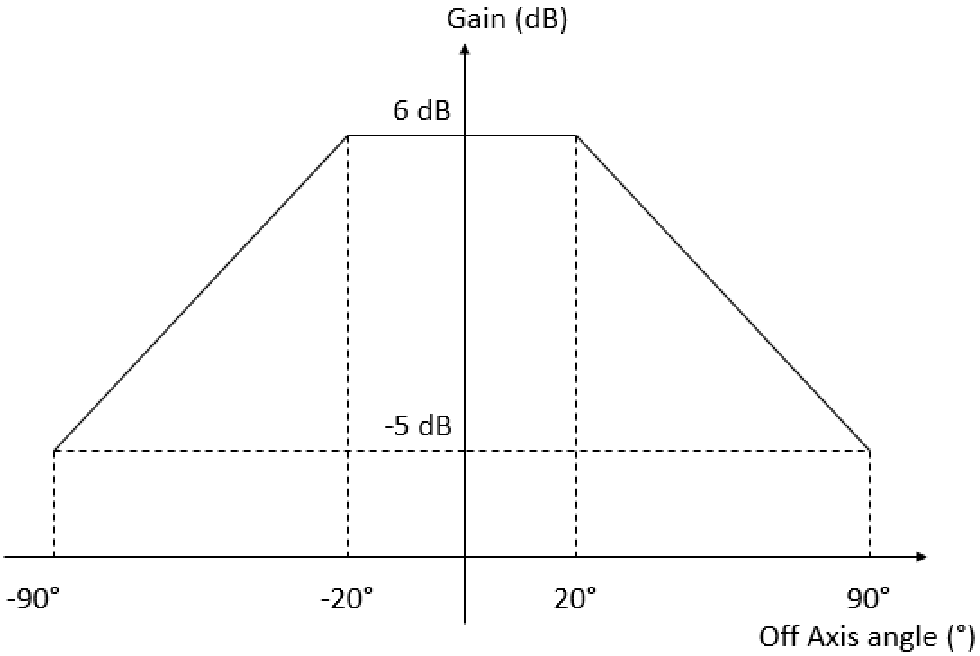

FIGURE 5.5: Communication gain assumed behavior

- Monitors the availability of the communication link depending on the communication gain. If the gain is under a chosen limit the communication is considered as unavailable and the RF card model is not able to process TM or TC. Otherwise the rover can communicate with the S/C,
- If the distance between the MMX S/C and the rover exceeds a given distance the communication link is considered lost,
- In descent mode the communication is considered possible until the distance with the S/C exceeds 300 m.

III. MMX S/C antenna

This model has the same behavior and parameters as the rover antenna, but from the S/C point of view.

IV. Rolbox

- Receives the TC provided by the user of the simulator (equivalent of the ground control segment from a functional point of view),
- Transmits this TC to the MMX S/C antenna model using the related communication protocol,
- Receives the rover TM and decrypts it,
- Shows the decrypted TM message in the simulator interface.

The architecture of the communication model is summed up in figure 5.6.

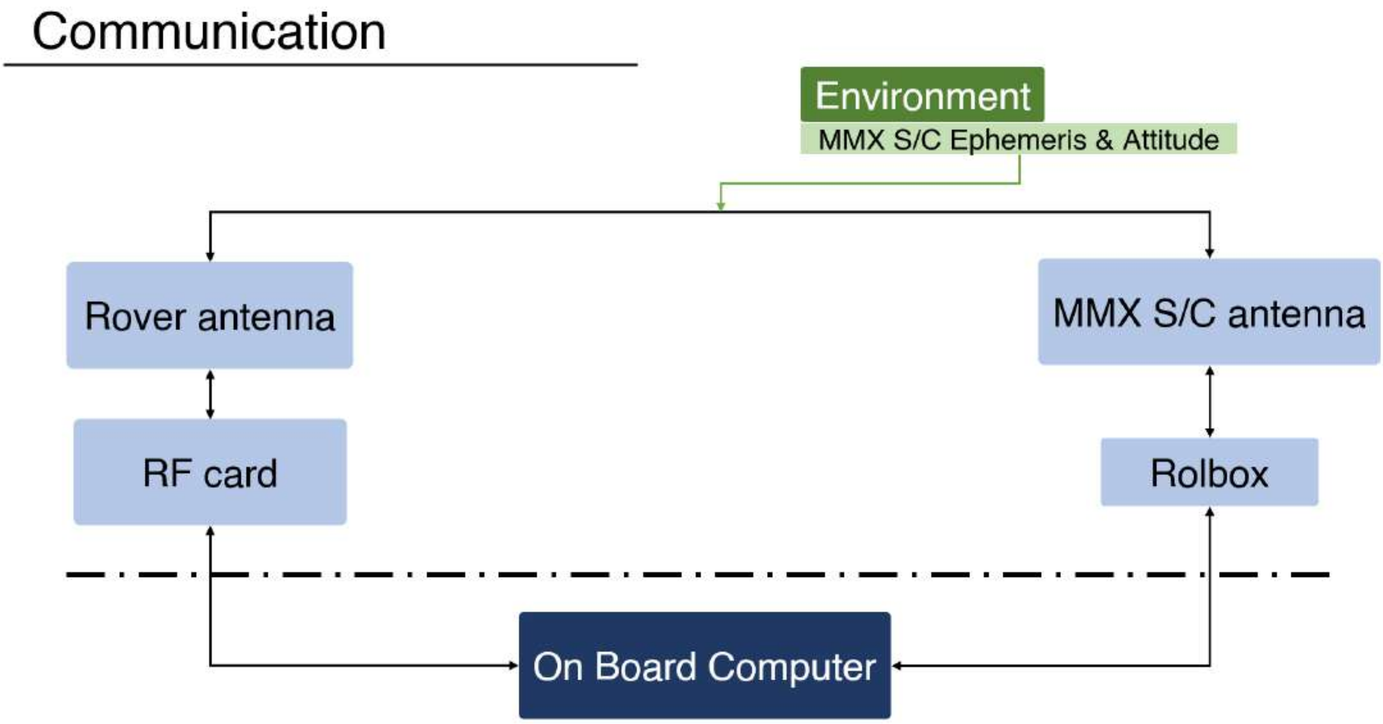

FIGURE 5.6: Communication model architecture

5.3 Science

RAX, MiniRAD and the Wheel Cams are grouped in the science section.

I. RAX

- Receives order to operate generated by the OBC using the related communication protocol (SpW),
- Operates the measurement only if:
  - The shutter is open,
  - The ambient temperature of RAX is in the acceptable range,
  - The underbody height of the rover is adjusted to the needed focus distance,
  - The front Wheel Cam LED is turned on.

  If one of these conditions is not satisfied the model generates an error signal specifying which one it is,
- Provides the state of RAX LED,
- Provides information on RAX laser:
  - Laser temperature,
  - Laser voltage,
  - Photo diode feedback,
- Provides information on RAX auto focus system:
  - Auto focus motor state (On/Off),
  - Motor position,
  - Focus position with +/- 10 mm precision,

- Provides information on RAX camera:
  - Camera shot parameters,
  - Camera temperature,
- Monitors data acquisition rate,
- Provides camera shots.

II. MiniRAD

- Receives measurement orders from the OBC using the related communication protocol,
- Operates the measurement only if the underbody height of the rover is adjusted to the needed focus distance,
- Configures calibration target temperature,
- Monitors calibration target parameters:
  - Current temperature,
  - Heating current.
- Configures sensor head target temperature,
- Monitors sensor head parameters:
  - Current temperature,
  - Heating current.
- Provides electronics temperature,
- Configures data acquisition rate,

III. Wheel Cams

- Receives camera shot order with camera shot parameters from the OBC using the related communication protocol,
- Provides camera shots parameters,
- Configures and monitors camera LED state,
- Provides camera shots with related communication protocol and compression process,
- The camera shots provided could come from two different generation processes: Picture stock, virtual camera positioned in the EDRES 3D environment.

The science model architecture is depicted in figure 5.7.

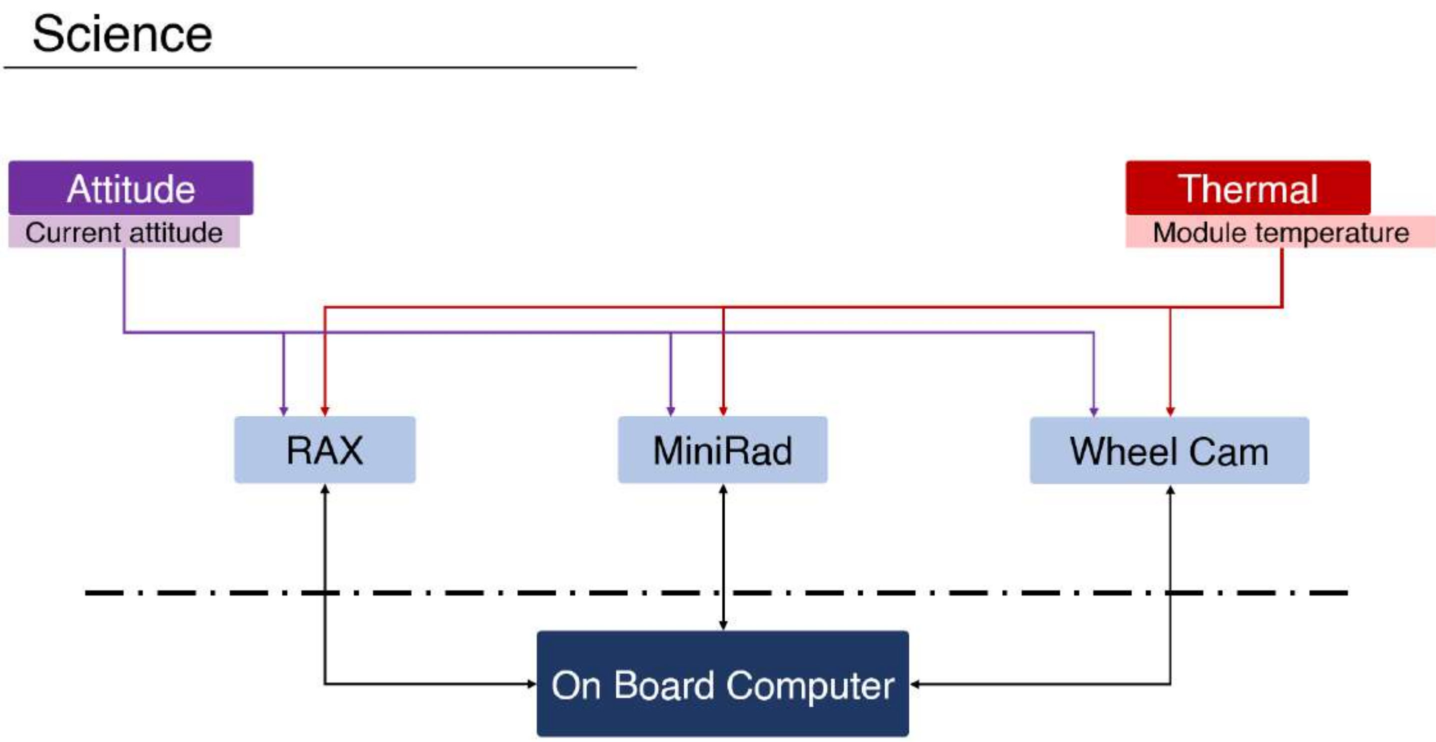

FIGURE 5.7: Science model architecture

5.4 Maneuver management

This group contains all the models needed to monitor the movement of the rover and all the associated needed information.

I. Locomotion

- Provides wheel motors rotation speed,
- Provides joint motors position.

II. Attitude sensors

- Sun sensor:
  - Provides four different currents and voltages of the sun sensor cells,
  - The sun attitude measurement must match the data provided by the sun ephemeris in the environment model.
- Gyroscopes
  - Provides three dimensional attitude coordinates.
- Accelerometer
  - Provides the coordinates of the acceleration vector acting on the rover.
- EDRES interfacing
  - The EDRES platform could be used in order to provide a dynamic behavior of the rover on a simulated ground,
  - This interfacing strategy should provide an actualization of the rover position on the ground at each calculation step of the simulator,

– The related attitude changes have to be confirmed by the accelerometer and gyroscope models.

III. NavCam

- Receives camera shot order with camera shot parameters from the OBC using the related communication protocol,
- Provides camera shots parameters,
- Provides camera shots with related communication protocol and compression process.
- The camera shots provided can come from two different generation processes: Picture stock, virtual camera positioned in the EDRES 3D environment,
- The camera shots generated must be coherent with the current position/attitude of the rover.

The architecture of the maneuver management model is resumed in figure 5.8.

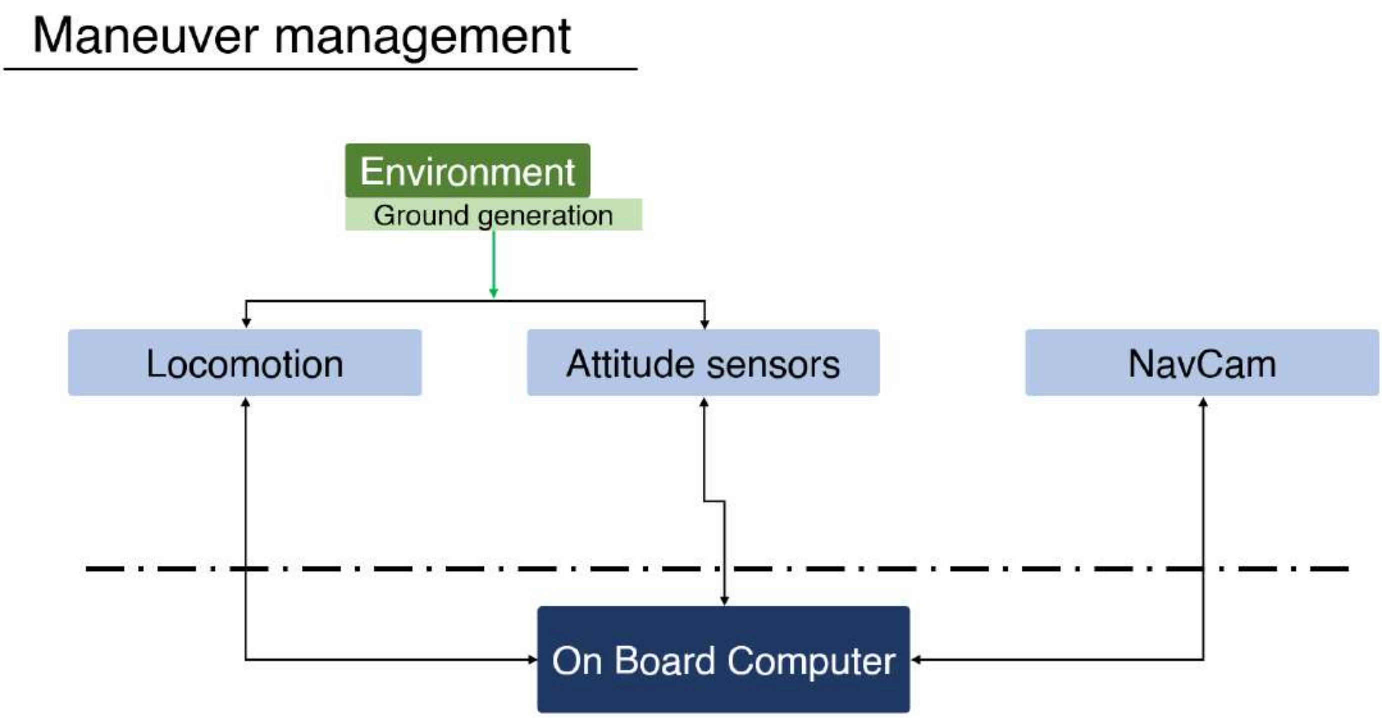

FIGURE 5.8: Maneuver management model architecture

5.5 Environment

I. Ground generation

- Provides a set of points in three dimensions. Once linked these points represent the ground. The ground generated contains different slope angles, giving a variety of practicable and not practicable paths,
- Allows to configure the distribution of practicable and not practicable slopes,

- Generates geological entities with random sizes and positions,
- Allows to configure the geological distribution density,
- The generated ground must be coherent with the rover's dynamic attitude computation,
- The ground generation could be done by the EDRES platform if its interfacing with the simulator is pursued.

II. Ephemeris

- Provides orbital parameters of the following bodies:
  - Sun
  - MMX S/C,
  - Mars.

  This means to provide the inclination, the longitude of ascending node, the eccentricity, the semi-major axis and the argument of periapsis of their orbit (called Keplerian elements).
  These elements are represented in figure 5.9:

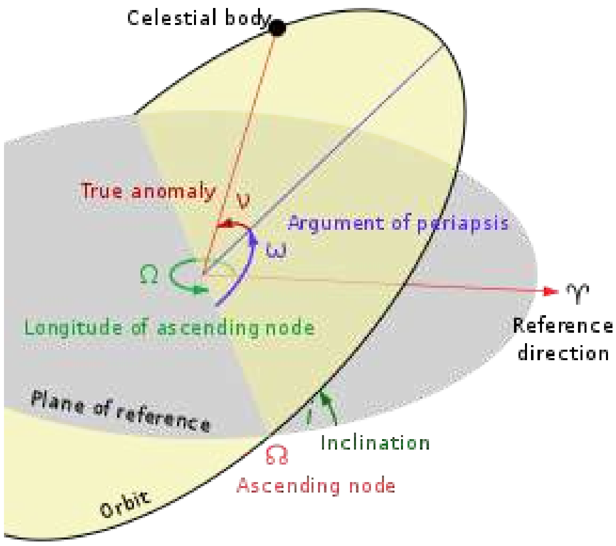

FIGURE 5.9: Keplerian elements of an orbiting body

- Provides the current position of these bodies along their orbit: their true anomaly.

III. Thermal model

- Provides the current temperature at the surface of Phobos. An example of model is shown in figure 5.10:

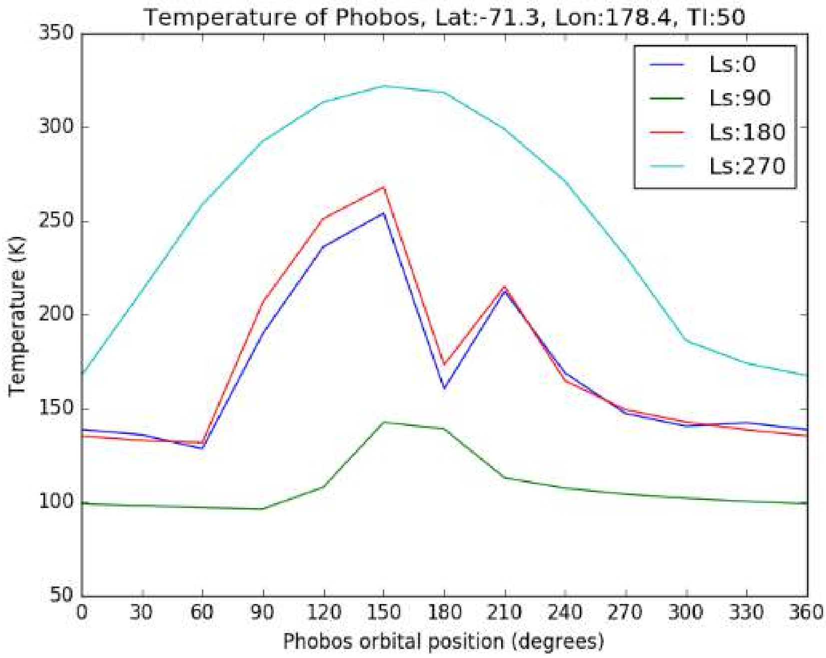

FIGURE 5.10: Phobos surface temperature model

[15] A more precise description of this model can be found in the appendix L.

- Provides a temperature distribution model inside the rover.

IV. Sunshine model

- Provides the available solar energy coming from the sun at the current position of the rover on the surface of Phobos,

  A model of this kind has been developed by National Aeronautics and Space Administration (NASA).

  > "It assumed the solar array is orientated parallel to the surface of Phobos without tracking the motion of the sun. The results account for effects of solar radiation intensity, exposure time, and incident angle of the sun light. Similar to the exposure time, the available energy changes from one season to another. Figure 5.11 shows four instances of the surface available energy (fixed array) per unit area for one Phobos orbit around Mars at equinoxes and solstices."[16]

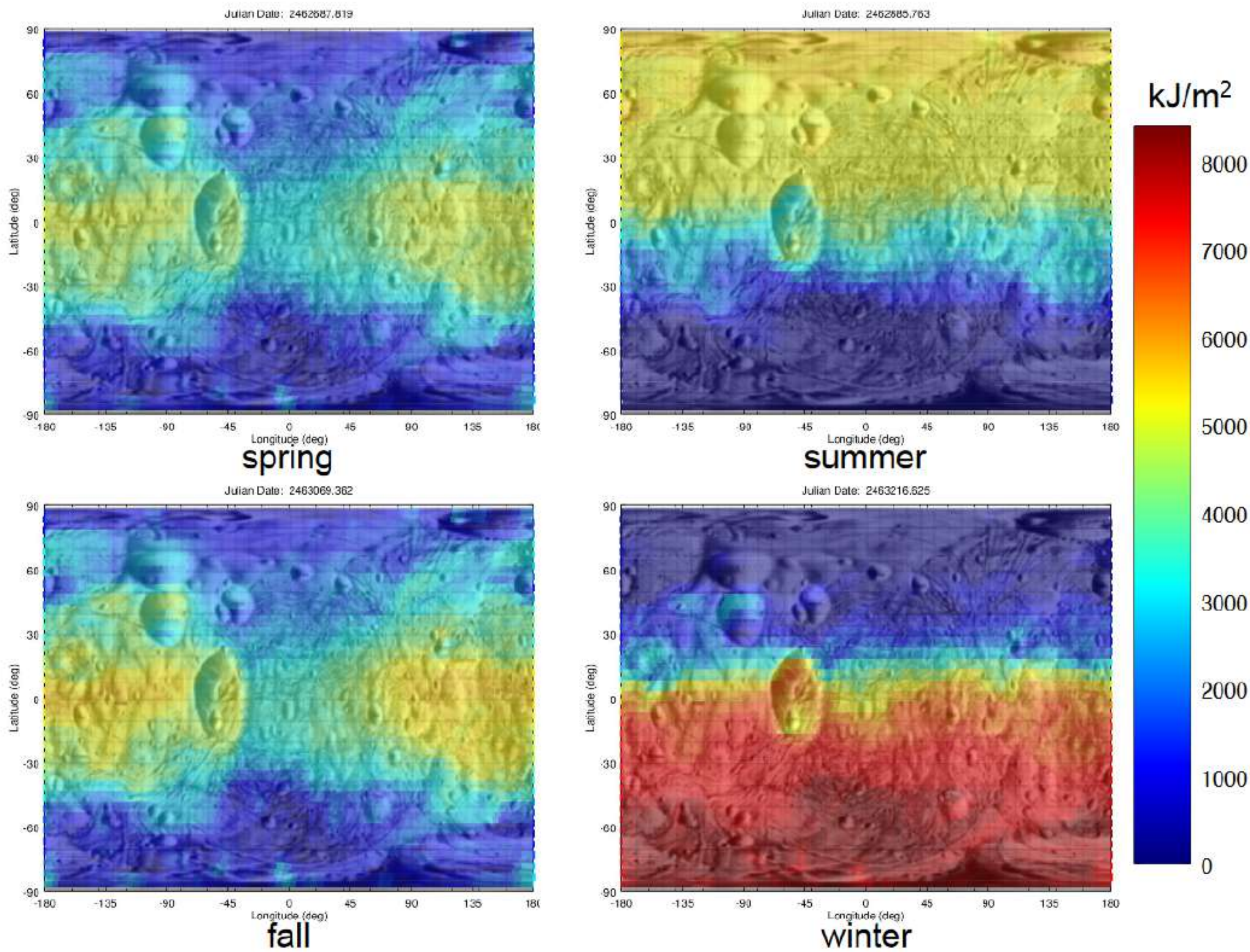

FIGURE 5.11: Available energy per unit area of solar array

The model shown in figure 5.11 gives an idea of the range of temperature at the surface of Phobos.

Figure 5.12 resumes the architecture of the environment model.

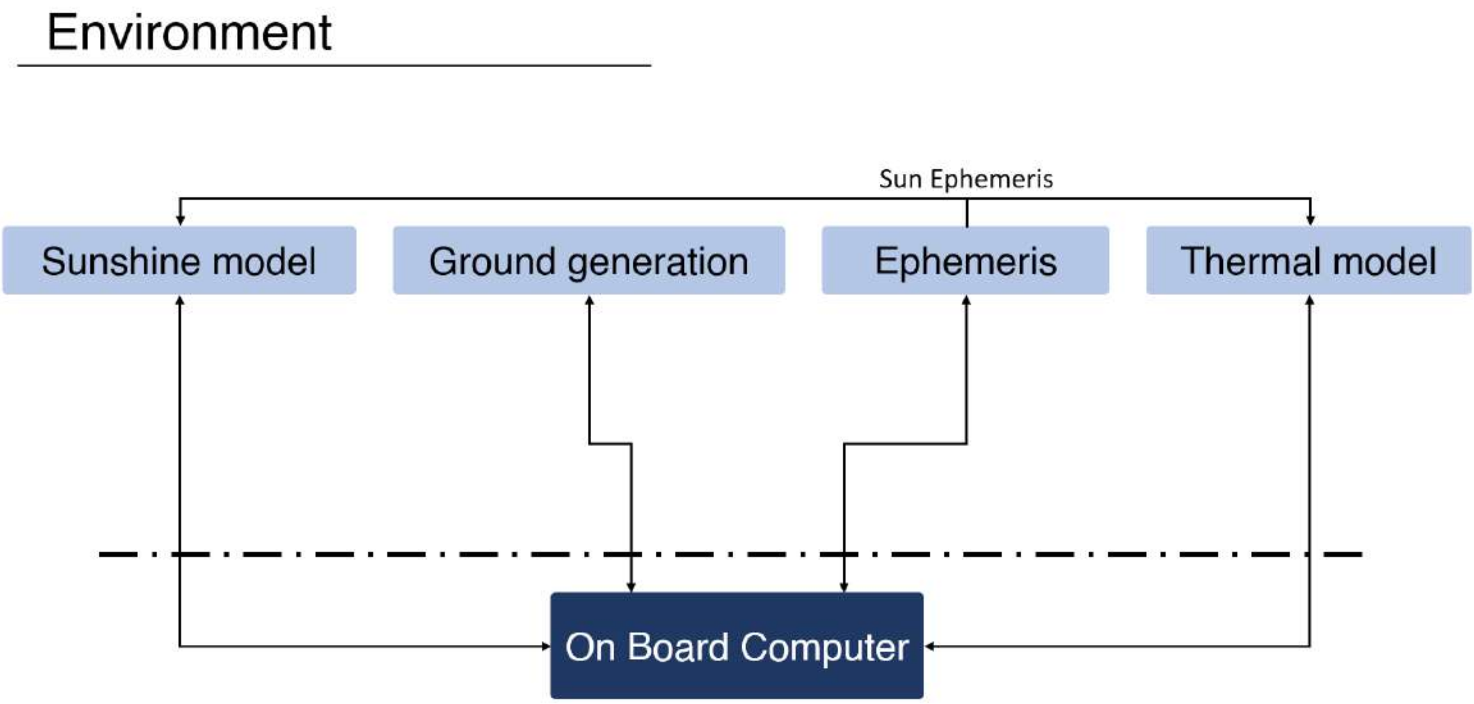

FIGURE 5.12: Environment model architecture

5.6 Thermal control

I. Thermistors

- Generates temperature signals with the related communication protocol for the following sub-systems:
  - two for the locomotion group,
  - five for the various shutters HDRM,
  - two for the HDRM,
  - ten for the thermistors of the thermal control loop,
  - six for the solar arrays HDRM,
  - two for the MECSS HDRM.

  ,
- The temperature signals generated must be coherent with the current values predicted by the thermal model,

II. Heating process

- Generates a thermal control law to simulate the heating process produced by the MMX S/C during the cruise phase,
- Provides the heating current used in the heating process of the locomotion part, the HDRM and the shutters,
- May generate the impact of a heating system if necessary.

The architecture of the thermal control model is summed up in figure 5.13.

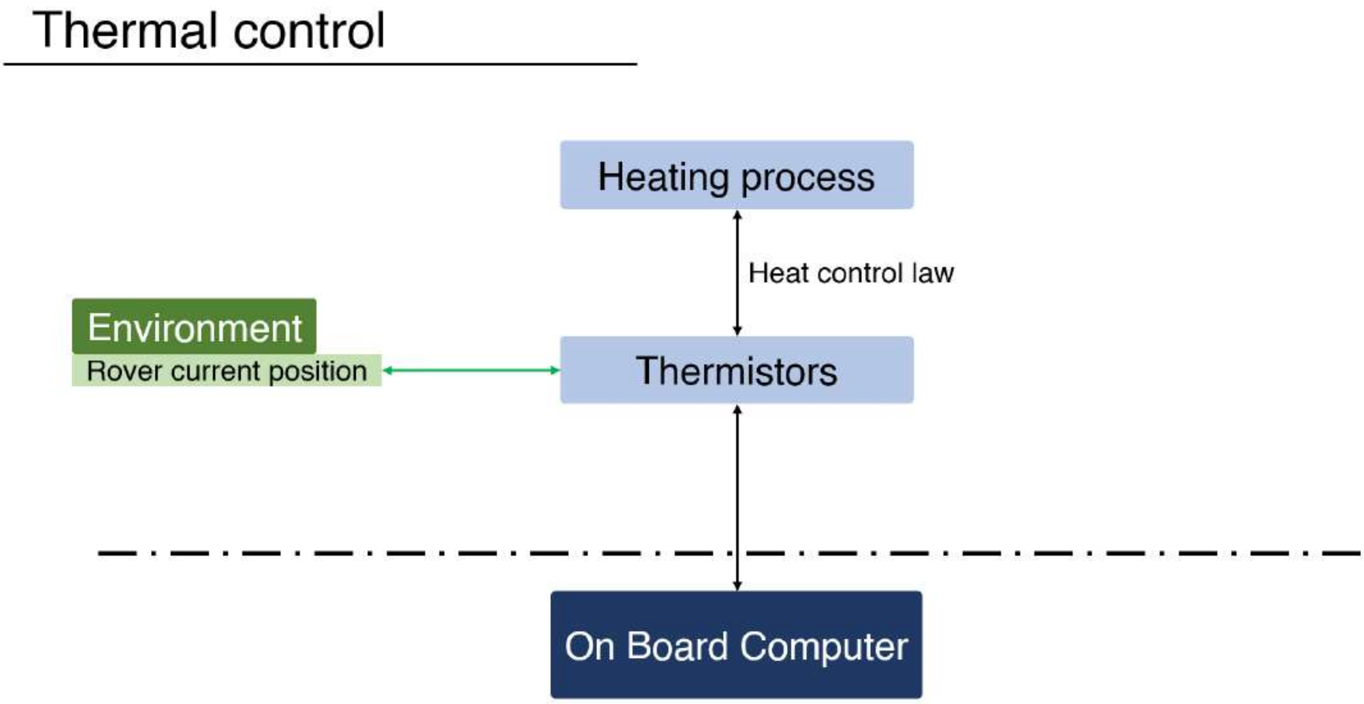

FIGURE 5.13: Thermal control model architecture

5.7 Mechanism management

I. HDRM

- Generates released/not released signals with the related communication protocol,
- Once a "released" signal has been generated, no other signal can be sent from the same HDRM.

II. Shutters

- Generates an open/closed signal with the related communication protocol,
- Except the RAX shutter, all the other ones within the system are for single use. Therefore once an "open" signal has been sent no other signal can be sent.

III. MECSS

- Generates the separation signal needed to confirm the separation between the S/C and the rover,
- Allows to configure the power provided by the MMX S/C to the rover during the cruise phase,
- Generates a signal giving the current attitude and position of the S/C in order to initialize the attitude computation of the rover. Provides in the same signal the delta V provided to the rover by the S/C.
- The attitude and position provided must be coherent with ephemeris provided by the environment model.

The architecture of the mechanism management model is summed up in figure 5.14.

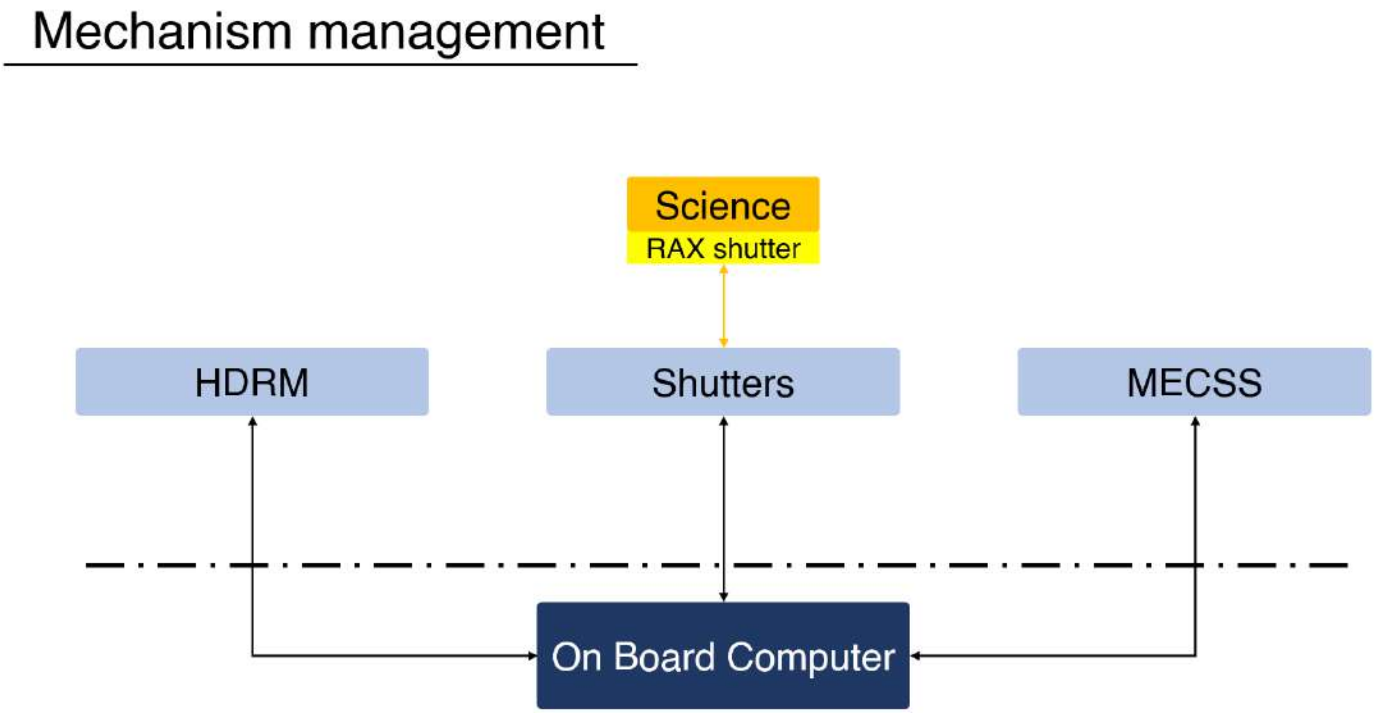

FIGURE 5.14: Mechanism management model architecture

Chapter 6

Conclusion

Space projects stand out from other engineering fields because the products designed need to work at their optimal performance level from the first time they are used with almost no margin of error. Time, cost, and technological constraints also makes it one of the most demanding sectors in terms of efficiency. A solution to this high demanding situation is to simulate the system with a very high level of fidelity in order to predict its behavior as well as possible. The objective of a simulator is not only to depict the system itself but also the way it works.

As shown through this thesis, the design quality of this simulation process has a direct impact on the validation of functional chains within the rover.

But the fidelity of the simulator is sensible to project characteristics such as its budget, its human resources and its timeline. Moreover in space projects, it is usual for industrial stakeholders to provide additional models to simulate the system produced. But rovers are not classical space projects and therefore the lack of documentation was sometimes a slowing factor.

The architecture derived in this thesis is representative of the MMX rover from a system and functional points of view. It ensures the viability and the relevance of future simulation campaigns and is based on the available documentation. This architecture is composed of seven simulation groups together with their interactions and takes into account the simulator development platform used at CNES.

Important discussions that could change the simulator architecture are still undergoing. The interfacing with another simulation platform called EDRES could change the way the simulator gets picture from the simulated ground and manages the dynamic of the rover. There is also an option to connect the real communication hardware to the simulator instead of using communication models. As long as this changing are transparent from a functional point of view they don't question the viability of the derived architecture.

The following step consist of the development of the different models used. It will be the base of development for validation simulators and is the topic of the next internship pursued by a new trainee at CNES.

Once fully developed the simulator will ensure the validation of the flight software and the training of operation teams. These are major aspects that will guarantee the viability of the system.

Appendix A

Motors wiring

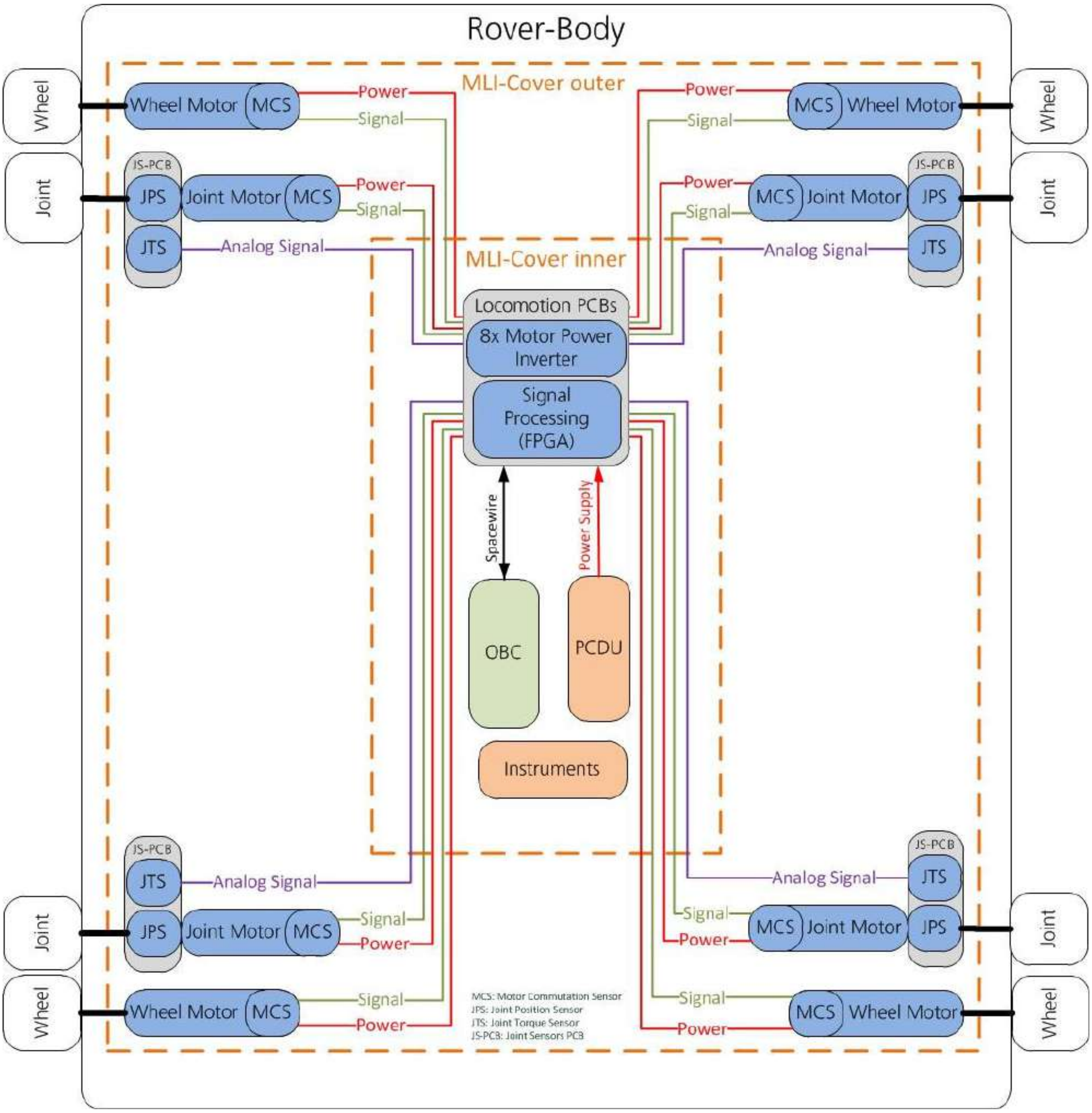

FIGURE A.1: Motors wiring

Appendix B

Vibration study

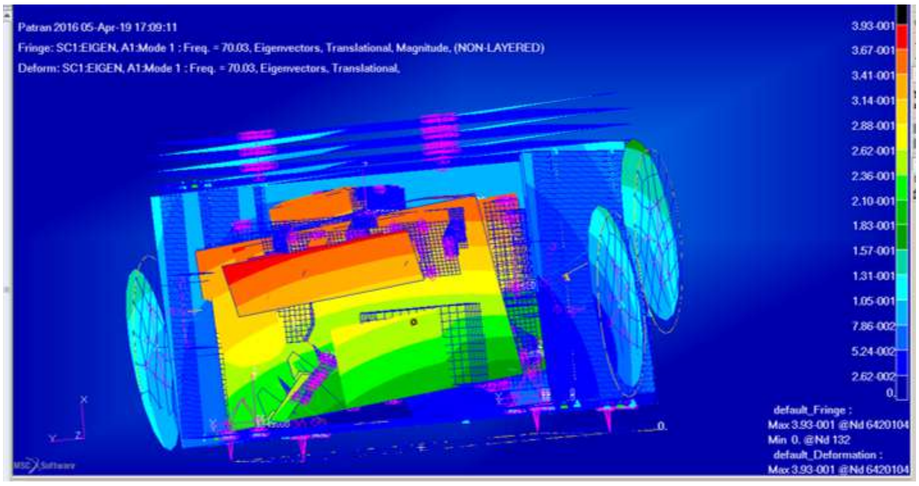

FIGURE B.1: 1st global mode damped

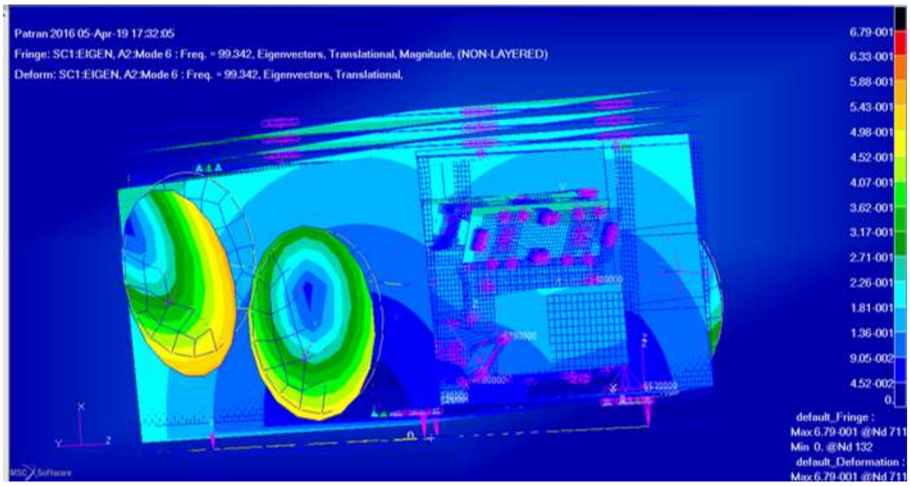

FIGURE B.2: 1st global mode stiff

frequencies [Hz]		
damped	stiff	remarke
70	-	y-direction
73	-	z-direction
85	-	x-direction
91,6	91	wheel
91,7	91,5	wheel
92	91,9	wheel
-	92,6	slightly y-direction
94	93,9	wheel
-	99	y/z-direction
106	107,3	wheel
116	117,24	wheel
117,2	117,7	wheel
117,4	-	wheel
119	119,6	Wheel
122	121	Wheel
123	123	Wheel
123,6	124	Wheel
124,7	125	Wheel
-	129	x-direction

FIGURE B.3: Study results

Appendix C

MECSS connections

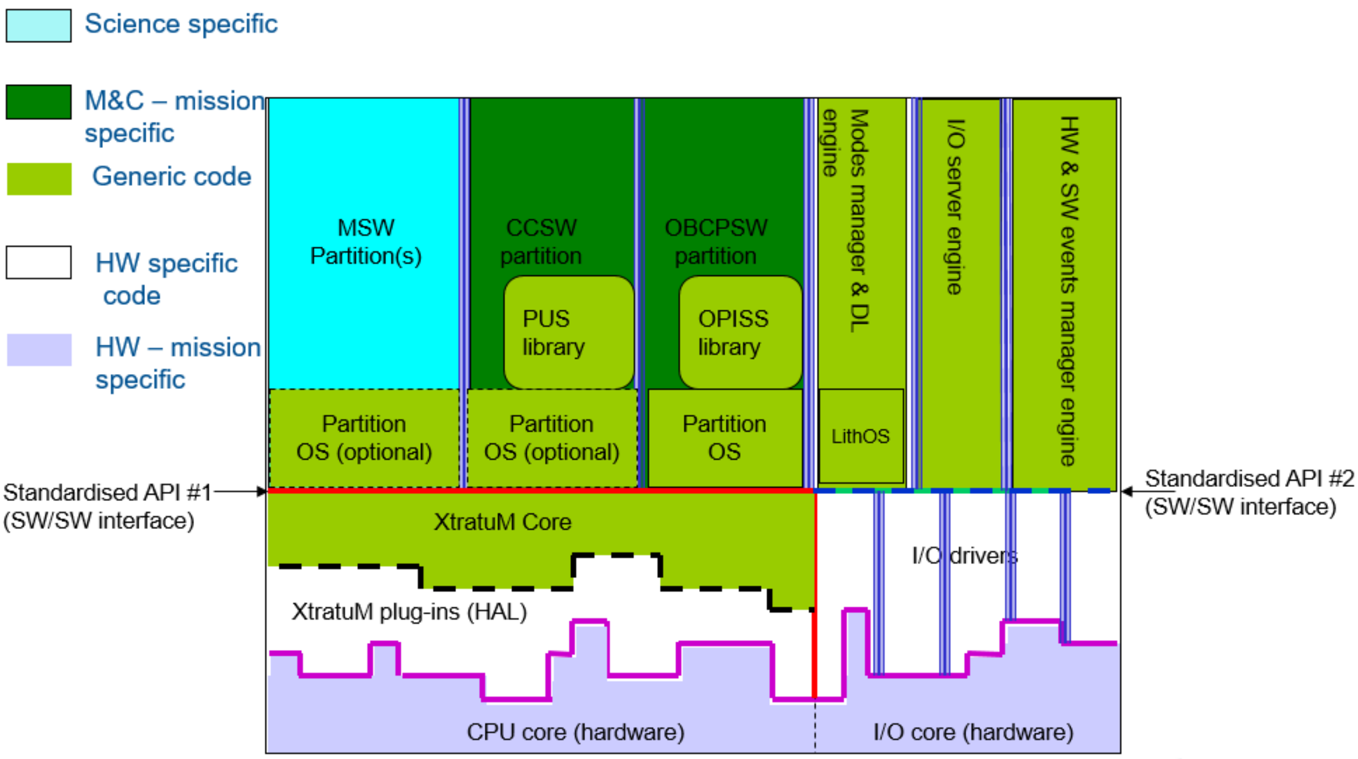

FIGURE C.1: LVCUGEN structure

Appendix D

MECSS connections

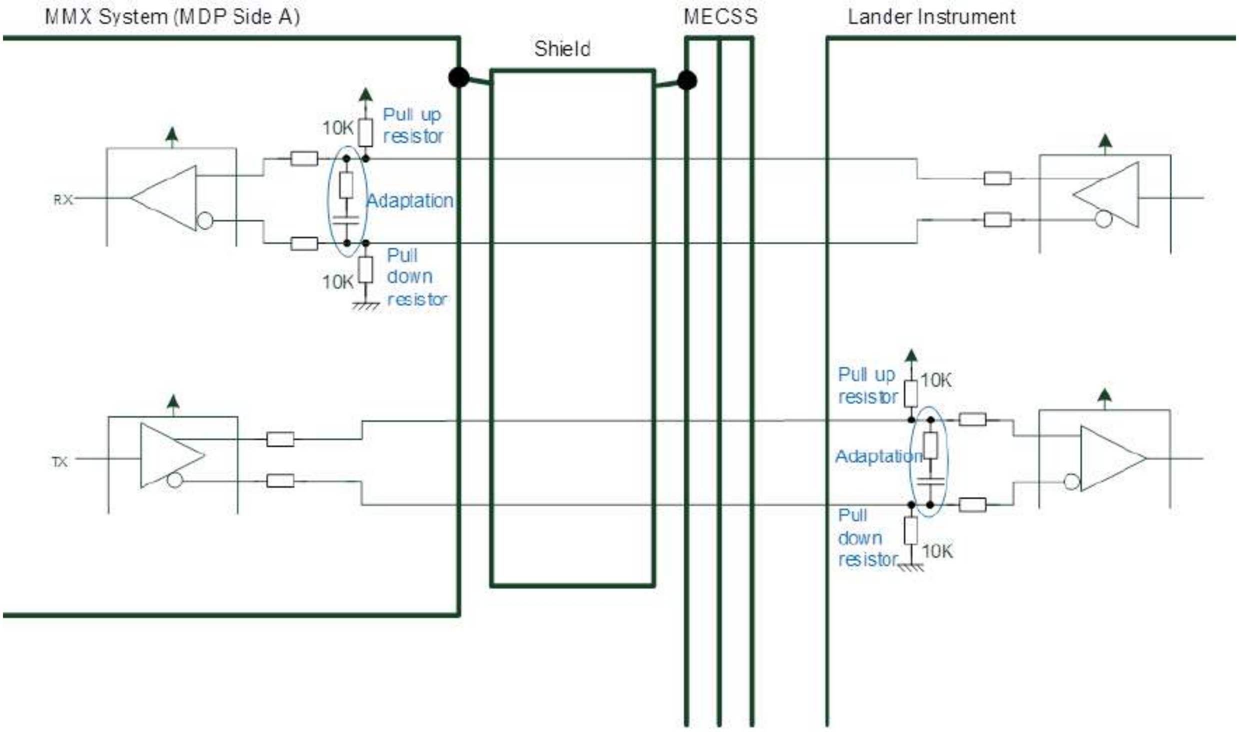

FIGURE D.1: Detail of the connections between the rover and the MECSS platform during cruise phase

Appendix E

Software Modes/Phases

Different modes will be used during each phase of the mission depending on its associated objectives. The following figure resumes the phases of the mission:

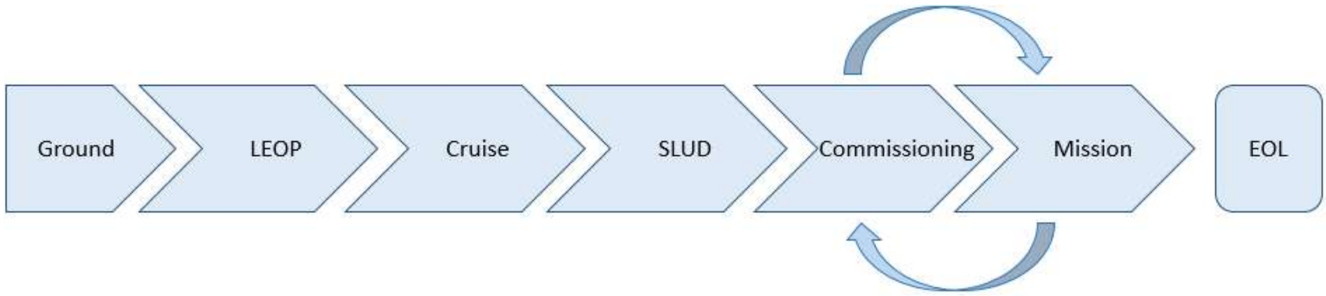

FIGURE E.1: Mission phases

The following part sums up these different modes [17]:

- Assembling Integration and Testing (AIT)

  The rover is able to use its communication capabilities (protocol level, and the whole equipment TM/TC plan). There's no Attitude Control sub-System (ACS) loop, the gyros or the sun sensor can be on, generating telemetry, but no attitude computation is made.

- Off

  In this mode, the OBC is not powered on: there's no software mode involved, no ACS mode either.

- Cruise

  In CRUISE MODE, the rover is powered by the spacecraft, and its functionalities are equivalent as in the AIT mode: the equipment can be switched on or off for health check tests or calibration (for the gyros or MiniRad). The rover can not autonomously leave this mode; this requires a TC. This insures a double protection against the activation of the Separation Landing Uprighting and Deployment (SLUD) sequence on MMX spacecraft, for it requires both a ground TC and the detection of the separation for the rover to trigger that sequence.

- Descent

  A ground TC is sent to trigger the transition to DESCENT mode a few hours before separation. The presence of the umbilical link is polled cyclically. While still on the S/C, the rover transceiver is powered on by ground TC, and so are the attitude sensor and the locomotion sub-system. Once the separation is detected, a time-out is initiated. A pre-determined sequence of NavCam pictures and telemetry transmission is started, the attitude measurements are looped on a high frequency basis. Once the timeout is over, the rover goes to UPRIGHTING & DEPLOYMENT mode.

- Uprighting & deployment

  When the rover enters in UPRIGHTING AND DEPLOYMENT mode, it will perform several legs movement to get up. The complexity of the succession of movements depends on which side the rover will fall on. It ends either on a success criteria, or a low battery alarm. In both cases, the solar arrays deployment is triggered.

- Safe

  In this mode, the rover is not moving anymore. The battery pack is not charging, and can last up to 72 h. Except for the RF communication chain all of the unnecessary equipment are off. In case there is no RF communication programming anymore on-board the rover powers its transceiver on every X hour for a duration of 20 minutes. During this period it downloads HKTM.

- Idle

  This mode charges the battery. At the end of any scientific or roving session, a TC "go to IDLE mode" is sent. This causes the rover to trigger the end of the previous activities, the sun pointing sequence and eventually, the transition to IDLE mode.

  In IDLE mode the rover is mainly waiting to execute its coming programming, while charging its battery pack.

- Driving

  According to ground TC orders the rover starts rolling. Wheel Cams and NavCam may record pictures or movies on ground TC order as well.

- Navigating

  In NAVIGATING mode, the OBS schedules the perception of the environment and the appropriate locomotion sequence. It contains two different navigation partition, one from the DLR, the other from CNES. For both cases the NAVIGATING mode can insure three different roles:

  - Commissioning
    The navigation partition is active but the driving orders only come from the ground,
  - Autonomous sub-mode
    The navigation is active and the driving orders only come from the navigation,
  - Re-compute sub-mode
    The navigation is active, it uses the NavCam pictures took earlier in roving phase to produce a navigating sequence.

- Science

  SCIENCE mode allows MiniRad and RAX to be powered on and make measurements. The locomotion sub-system may change the attitude of the rover for RAX auto focus sequence. The position of the rover with respect to the surface of Phobos is not changing in this mode.

- Bye-Bye

  This is the end-of-life mode, the rover is definitely turned off.

The use of each mode depending on the mission phase is summed up in the next figure.

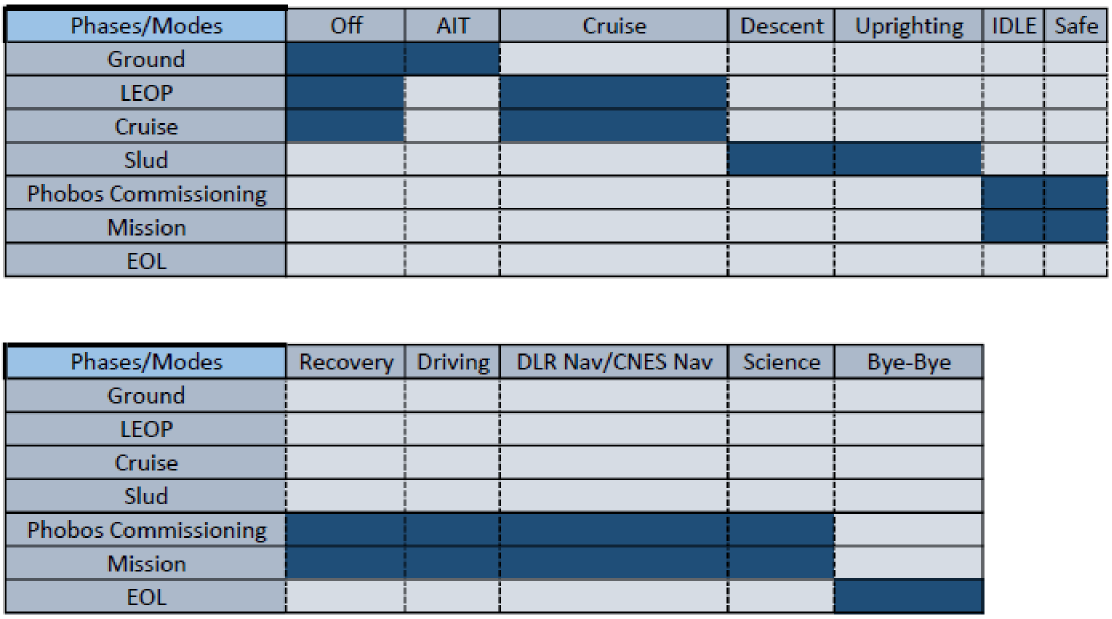

FIGURE E.2: Software Modes/Phases

Appendix F

Functional chains

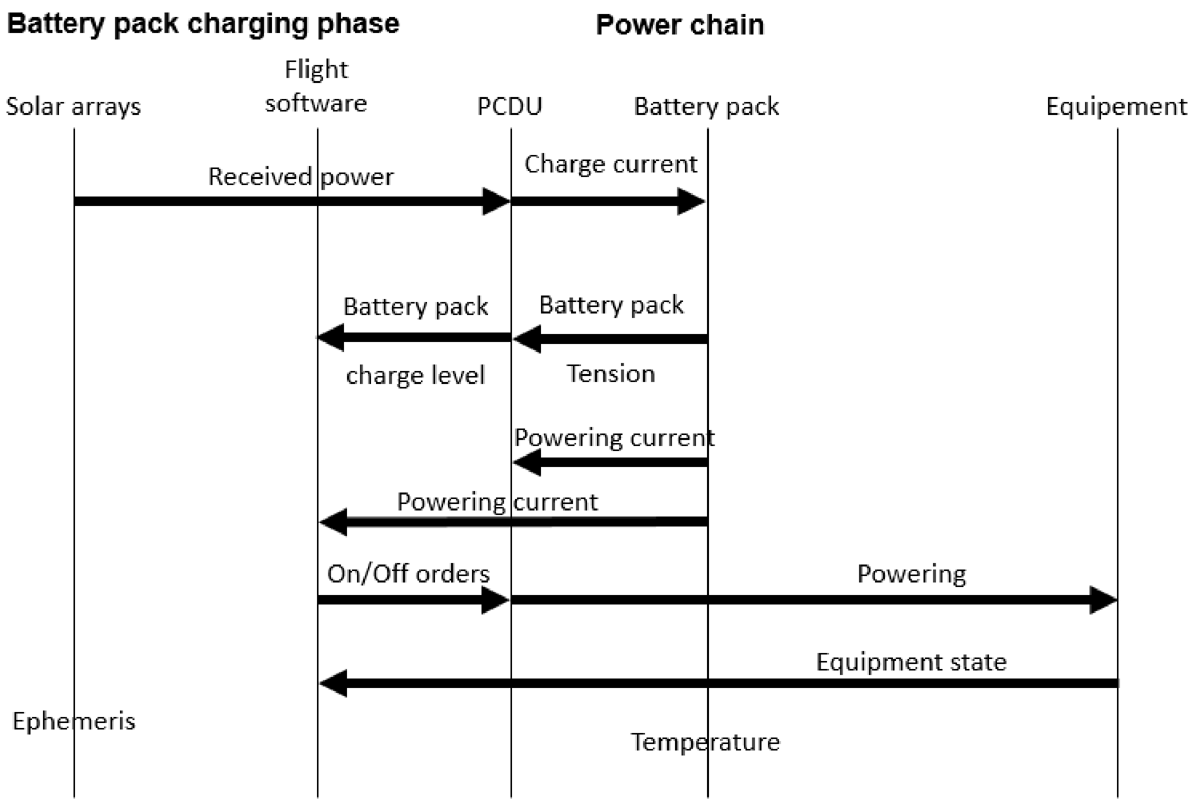

FIGURE F.1: Battery charging chain

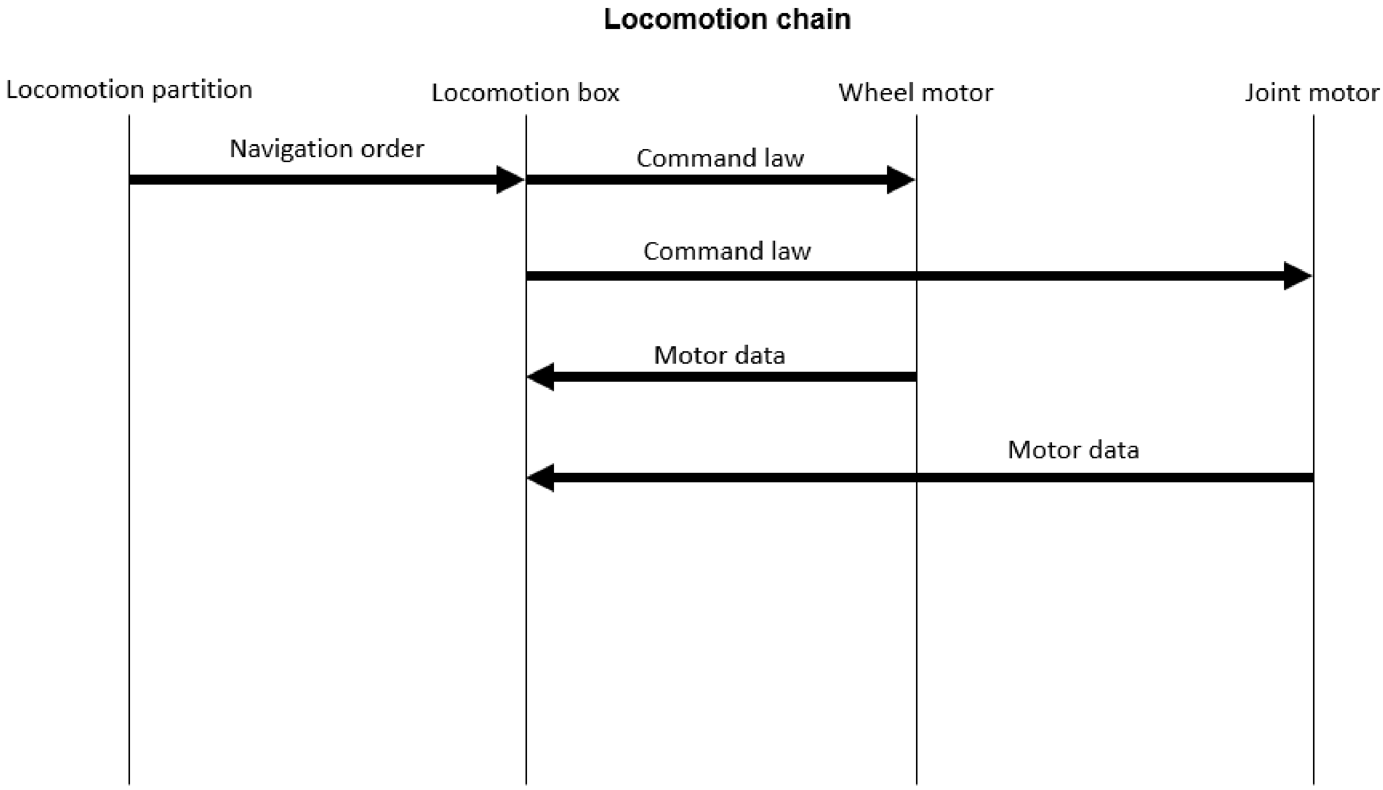

FIGURE F.2: Locomotion chain

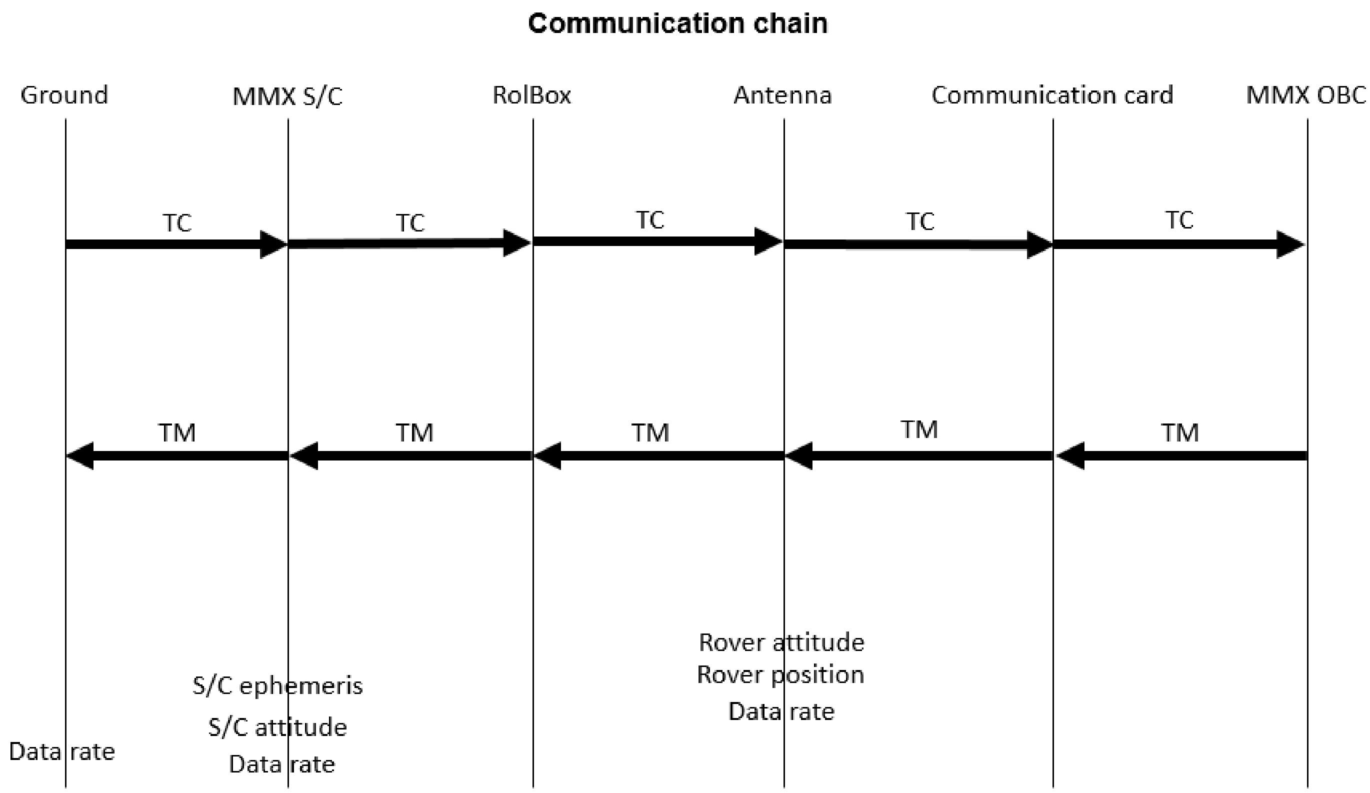

FIGURE F.3: Communication chain

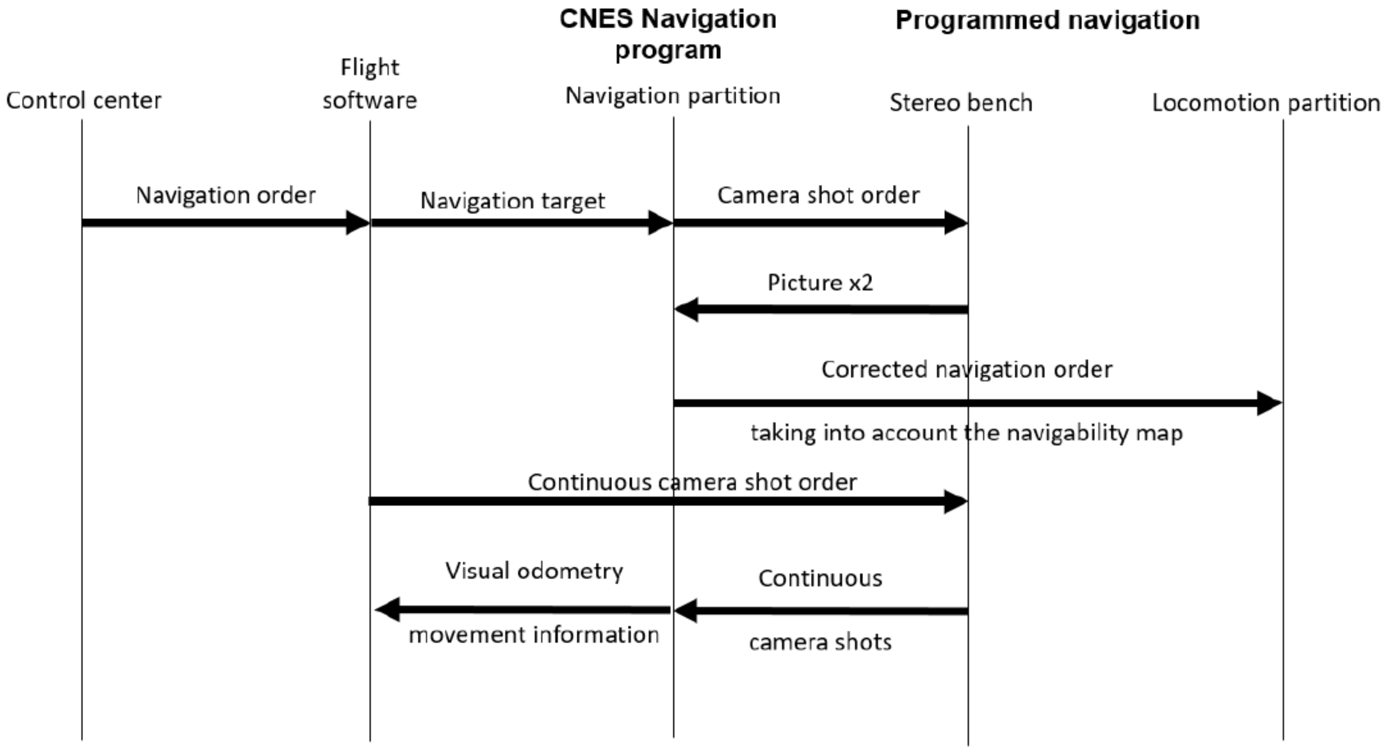

FIGURE F.4: CNES navigation chain

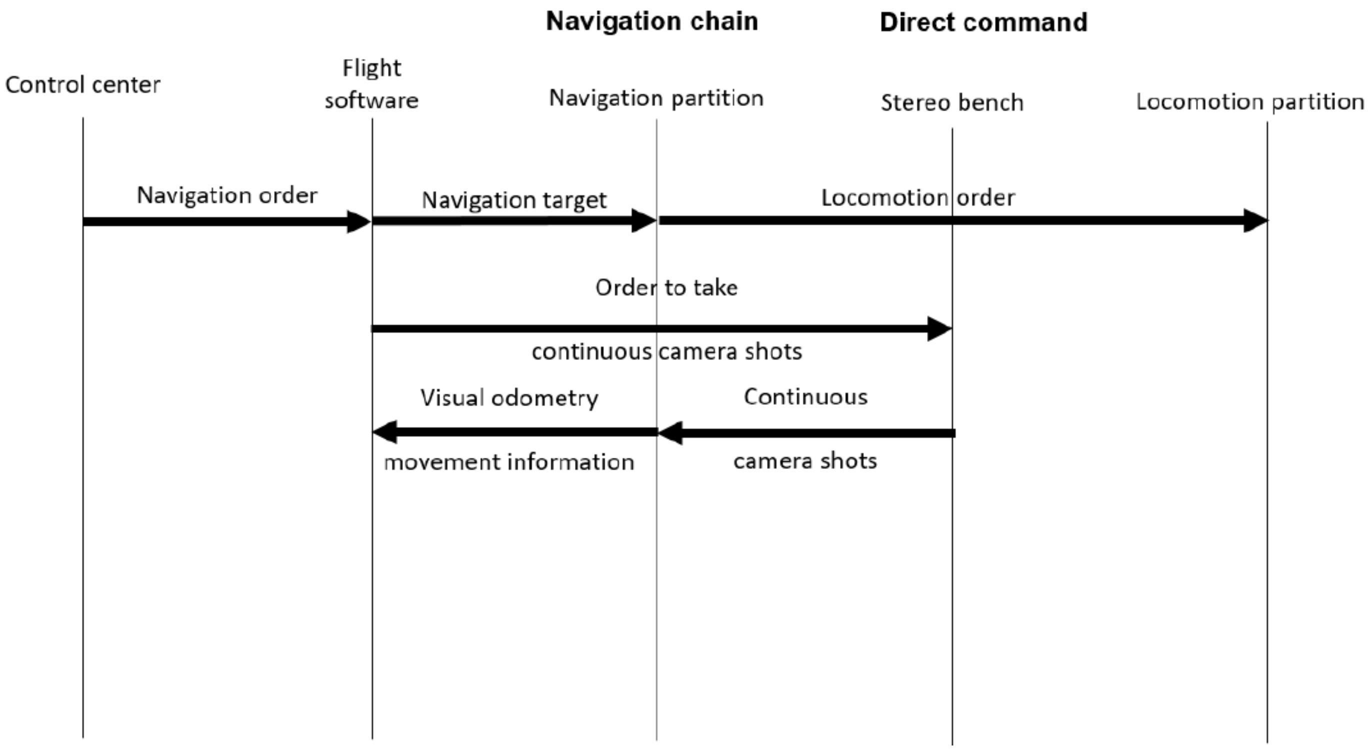

FIGURE F.5: Navigation chain direct command

Appendix G

OBC details

I. Processor

The MMX rover OBC is equipped with two Arm 9 processors. These processor are considered as quite powerful when compared to the other processors used in modern spatial projects.

> "In term of computing power, the rover will be much more capable than the other existing rovers. The foreseen on-board-computer [...] embeds a System-on-Chip Zynq 7045 from Xilinx. One of its characteristics is to implement a 900MHz dual core Cortex A9 with Neon^{TM} FPU.In term of memories, the board implement 1 GBDDR3 RAM and up to 256Gb NAND Flash.This CPU board has been hardened by design since the beginning of the development (Latch-up protection, several level of supervision).7.ROB"

[2]

This calculation speed/power is needed to run the DLR navigation partition.

II. FPGA

> "Field Programmable Gate Arrays (FPGAs) are semiconductor devices that are based around a matrix of configurable logic blocks (CLBs) connected via programmable interconnects. FPGAs can be reprogrammed to desired application or functionality requirements after manufacturing. This feature distinguishes FPGAs from Application Specific Integrated Circuits (ASICs), which are custom manufactured for specific design tasks."

[18]

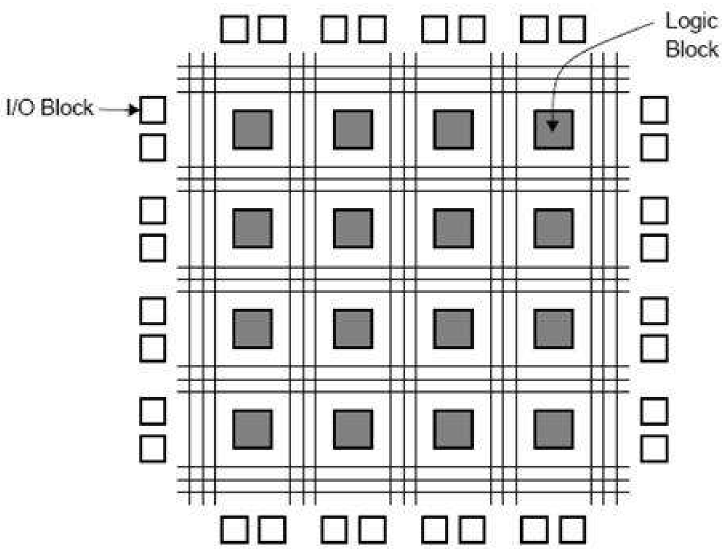

FIGURE G.1: FPGA structure

FPGA were originally used to compute simple operations which can be carried out in parallel. While the processors were used to compute more complex tasks. But more recent considerations and improvements in this technology are changing the usage of this elements.

> "The application of FPGAs has moved from simple gluelogic to complete subsystem platforms that combine several real time system functions on asingle chip, even including microprocessors and memories"

[19]

For the rover, the FPGA ensures low level interfaces protocols, and memory access.

Beside the FPGA used in the OBC, another one can be found in the stereo bench. This one ensures the picture compression needed for NavCam shots.

Appendix H

Interviews form

DSO/AVI/VS

Person – Department/topic

Case followed by : Maxime Olivari
E-mail : maxime.olivari@cnes.fr
-

Toulouse, 20/11/2019
N/Ref : RF - 1

Subject: MMX core team simulation needs

- What is the scope of your activities?
- What are the sub-systems involved in your daily work?
- What are your most important validation needs (on a software perspective)?
- Do you already know any existing simulation technologies that could satisfy your validation needs?
- What are the means interacting with this technologies?
- What fidelity level can be considered as acceptable concerning your validation needs? (what elements needs to be simulated? if they are simulated, how well do they represent the reality?)

Maxime Olivari

Copy(ies) : Person

Appendix I

Avioncics architecture

The avionics architecture sums up the different communication protocols used in the rover. It also shows in a synthetic way the different sub-systems involved and their possible links.

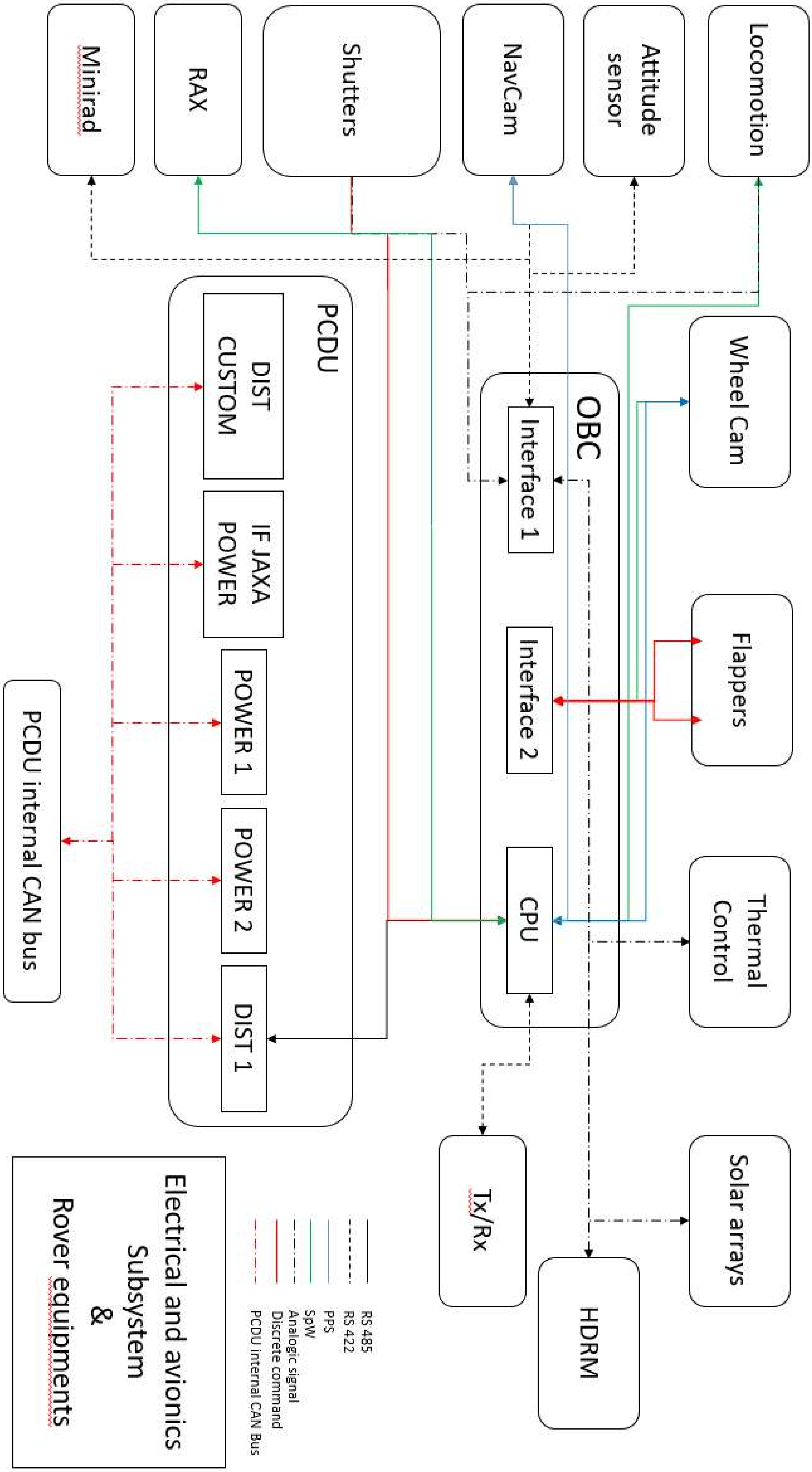

FIGURE I.1: Avionics architecture

Appendix J

Attitude sensors

The avionics architecture sums up the different communication protocols used in the rover. It also shows in a synthetic way the different sub-systems involved and their possible links.

I. Sun sensor The sun sensor parametrisation is summed up in the following figure:

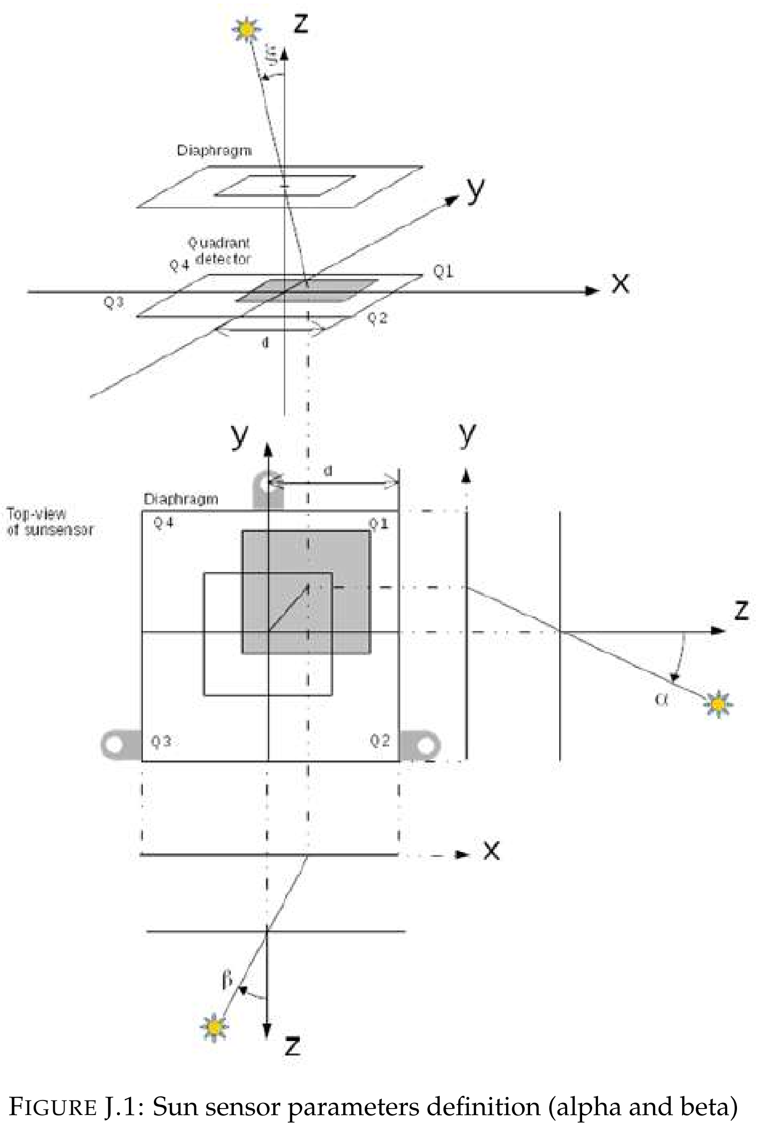

FIGURE J.1: Sun sensor parameters definition (alpha and beta)

The angular position of the sun can be linked to the solar flux received by each of the four quadrants via theses equations:

$$S_a = \frac{Q_1 + Q_4 - Q_2 - Q_3}{Q_1 + Q_2 + Q_3 + Q_4} = \frac{\tan(\alpha)}{\tan(\alpha_{max})}$$

$$S_b = \frac{Q_1 + Q_2 - Q_3 - Q_4}{Q_1 + Q_2 + Q_3 + Q_4} = \frac{\tan(\beta)}{\tan(\beta_{max})}$$

FIGURE J.2: Avionics architecture

II. Gyroscopes

Appendix K

Simulator design on BASILES platform

Rajouter au moins:

Editeur de modèle avec les différents champ à compléter Editeur de scenario Screen patrimoine les 4 grandes étapes

Appendix L

Mapping the Thermal Inertia of Phobos using Thermal Infrared Spectra and Thermophysical Modeling

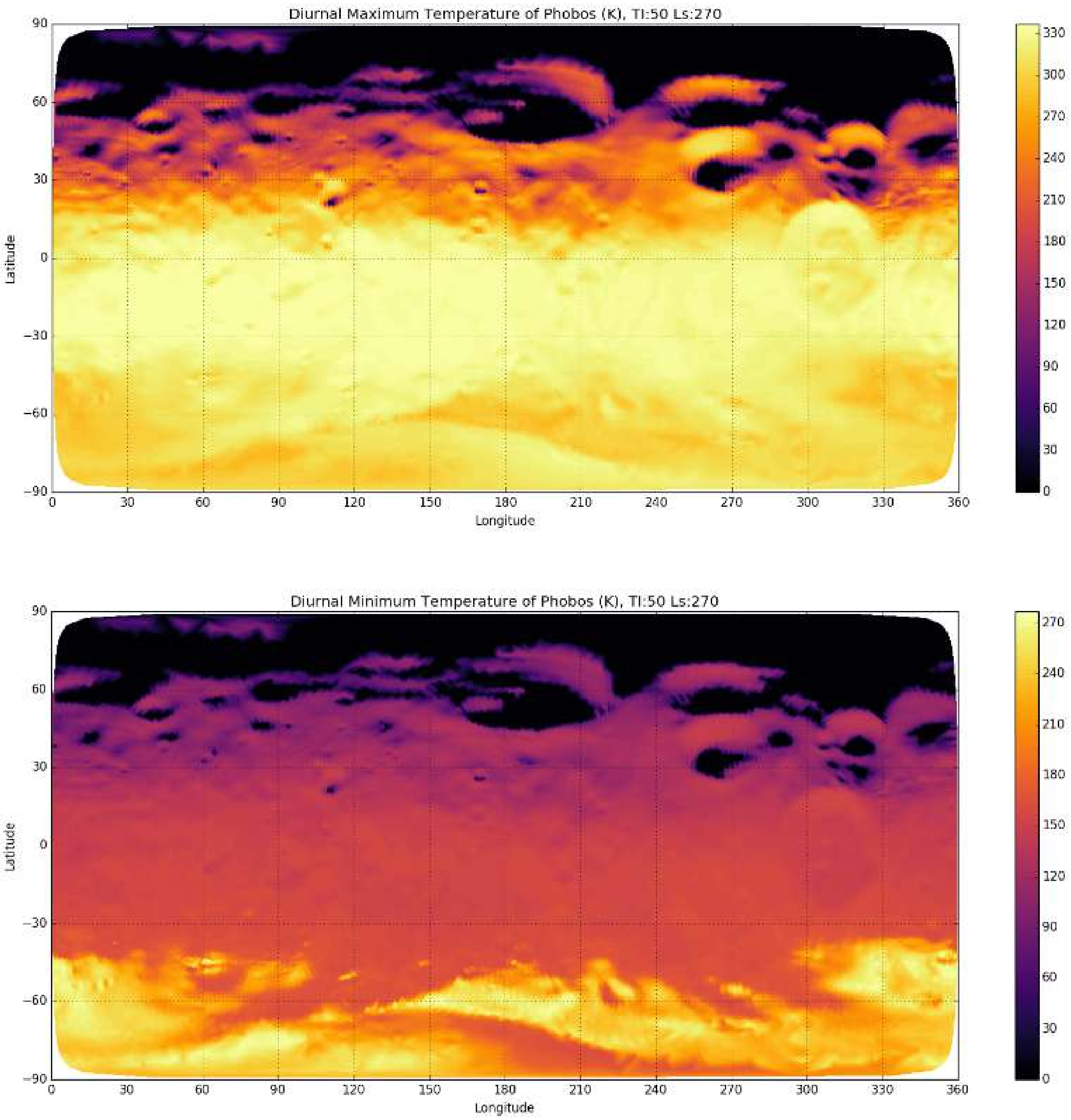

FIGURE L.1: Phobos surface temperature advanced model

[15]

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