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"THE CONCEPTUAL DESIGN OF THE TEAM ITALIA AMALIA MISSION ROVER, CANDIDATE FOR GOOGLE LUNAR X PRIZE CHALLENGE"

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ABSTRACT

The paper provides an overview of the conceptual design of the Lunar Rover conceived by Team Italia for the AMALIA Mission, candidate for the Google Lunar X Prize Challenge.

With this initiative, the X Prize Foundation intends to promote the involvement of private actors in the access to space, by endowing a prize to the first privately funded lunar mission covering a certain minimum distance on the Moon surface. Additional prizes are available in case of achievement of more challenging goals, like surviving lunar night, travelling for a longer distance, visiting areas of the first Apollo Missions.

Although the AMALIA Rover Subsystems are the typical ones of an Exploration Rover, their design is highly influenced by the above depicted mission context. The followed design approach is closer to the one of a commercial mission than to an Institutional Space Exploration Mission one. It has to be noted that, for being compliant with GLXP rules, at least 90% of funds required for competing in the Prize has to come from private or non-governmental sources.

The achievement of such challenging goals requires to adopt suitable technical and programmatic solutions, having the need to optimize costs and schedule while still maximizing the probability of success.

1. INTRODUCTION

The AMALIA (Ascensio Machinae Ad Lunam Italica Arte) Mission Rover described in the present paper is the mission element in charge of actually achieving the Google Lunar X Prize (GLXP) goal of covering a minimum distance of 500 m. on lunar surface by satisfying a set of well identified requirements set forth by GLXP Foundation. This goal has to be achieved before the end of 2012.

The Rover is designed, together with the other elements of the mission, by Team Italia, which is participated by the most important Universities and private players in the Italian aerospace landscape, including SME, small and large system integrators.

Team Italia currently includes the following members:

- AICA
- Carlo Gavazzi Space
- Politecnico di Milano
- Politecnico di Torino
- Techno System developments
- Thales Alenia Space – Italia
- Università di Napoli Federico II
- Università di Roma La Sapienza

ALTEC collaborates with Team Italia working, together with AICA, in the area of Ground Segment definition and operations

Team Italia participation to the competition was officially announced on February 21st 2008 at the 1st Google Lunar X Prize Team Summit that took place in Mountain View, Ca

The team members, leveraging on their experience acquired in the space sector and taking on the Google Lunar X Prize challenge, want to develop a new paradigm for the definition and the development of complex projects such as a planetary mission.

The Team Italia members are now working together for reaching the very challenging Google Lunar X Prize objectives and applying, at the same time, an innovative approach for the future Space Exploration Programs.

2. THE GOOGLE LUNAR X PRIZE

The Google Lunar X PRIZE is a $30 million international competition to safely land a robot on the surface of the Moon, travel 500 meters over the lunar surface, and send a specified set of images and data back to the Earth. Teams must be at least 90% privately funded and must be registered to compete by December 31st, 2010. The first team that lands on the Moon and completes the mission objectives will be awarded $20 million; the full first prize is available until December 31st, 2012. After that date, the first prize will drop to $15 million. The second team to accomplish the GLXP requirements will be awarded $5 million. Another $5 million will be awarded in bonus prizes. The final deadline for winning the prize is December 31st, 2014.

An additional $5 million in bonus prizes can be won by successfully completing additional mission tasks, such as roving longer distances (> 5,000 meters), imaging man made artefacts (e.g. Apollo hardware), discovering water ice, and/or surviving through a frigid lunar night (approximately 14.5 Earth days). The competing lunar spacecraft will be equipped with high-definition video and still cameras, and will send images and data to Earth, which the public will be able to view on the Google Lunar X PRIZE website.

The images and data to be sent back to the Earth are part of the so called MoonCasts. The MoonCast consists of digital data that must be collected and transmitted to the Earth composed of the following:

- High resolution 360º panoramic photographs taken on the surface of the Moon;
- Self portraits of the rover taken on the surface of the Moon;
- Near-real time videos showing the craft's journey along the lunar surface;
- High Definition (HD) video;
- Transmission of a cached set of data, loaded on the craft before launch (e.g. first email from the Moon).

Teams will be required to send a first MoonCast documenting their arrival on the lunar surface, and a second MoonCast providing imagery and video of the journey moving on the lunar surface. All told, the MoonCasts will represent approximately a Gigabyte of stunning content returned to the Earth.

3. AMALIA MISSION OVERVIEW

The AMALIA Mission Architecture foresees the development of two main elements: the AMALIA Lunar Lander (ALL) and the AMALIA Rover. Both elements are necessary to satisfy all the GLXP requirements. Their design has been implemented maximising, where applicable, the sharing of functions in order to limit the overall mass of the mission elements.

The selected mission scenario to approach the Moon Equatorial Zone, which is the target site of the mission, can be subdivided in the following phases:

- Launch phase - the AMALIA Lunar Lander is put by the launcher in a low altitude parking orbit (200-300 km, circular or slightly elliptic)

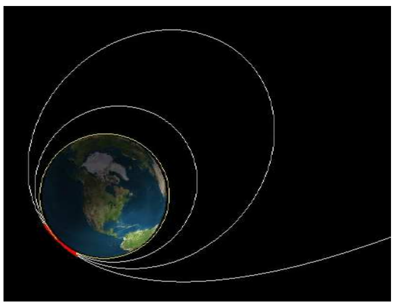

Figure 3-1 - Launch Phase

- Lunar Transfer Orbit (LTO) Insertion phase - the ALL begins the apogee raising and performs LTO insertion manoeuvres (typically three-burns)

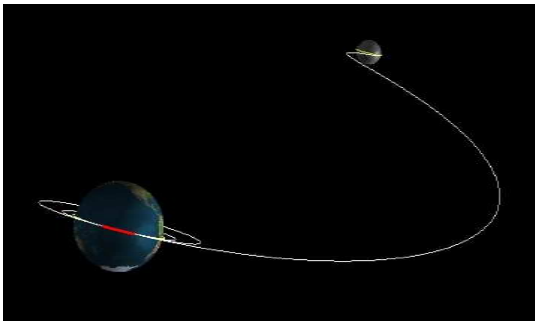

Figure 3-2 - Lunar Transfer Orbit Insertion Phase

- Lunar Orbit Insertion (LOI) phase - in proximity of the Moon, the ALL performs a Lunar Orbit Injection (LOI) manoeuvre to reach the target LLO

- Loiter and Landing phase - inserted in LLO, the ALL, after several orbits around the moon, begins the descent and landing manoeuvres

- Surface Operations phase - The AMALIA Rover performs its operations on lunar surface according to GLXP requirements.

4. THE AMALIA ROVER

4.1. Main AMALIA Rover Requirements and Design Drivers

Starting from the GLXP specific Requirements and challenge context and from the selected AMALIA Mission Architecture, it has been possible to derive the main AMALIA Rover Requirements and Design Drivers. The first main AMALIA Rover design driver is the landing location, foreseen at Moon Equator. This choice has been made considering two main aspects: the characteristics of the terrain and the possibility to land near a past Apollo Mission. In fact, the terrain at the Moon Equatorial Zone is very flat and with fewer obstacles than for example at the Moon South Pole, allowing increasing the performances of a mobile element as the AMALIA Rover. Moreover, the Apollo Missions have landed on different sites at Moon Equator, and the AMALIA Rover could have the possibility to acquire a picture of one of the Apollo Landers, satisfying the requirement of a GLXP Bonus Prize (imaging man made artefacts). The landing location implies severe requirements on the design of some AMALIA Rover S/Ss. In particular, landing at Moon Equator has an influence on the sizing of the Power S/S (e.g. due to the duration of lunar daylight/night cycle) and on the sizing of the Thermal Control S/S (e.g. due to the wide temperature ranges to which the Rover SSs are subjected).

Another important design driver comes directly from the Google Lunar X-Prize requirements: it is the distance of 500m that has to be covered moving on lunar surface.

This distance, together with the duration of the lunar daylight, implies several requirements on the AMALIA Rover locomotion S/S and Surface Operations. In fact, the AMALIA Rover will need to cover the 500m as fast as possible due to the reduced number of days available to perform the overall mission, having decided as baseline to cover the required distance within a lunar day.

Other Main AMALIA Rover Requirements and Design Drivers come from:

- Lander P/L mass capability - the AMALIA Rover has been designed in order to optimise and limit its mass
- Safety and reliability aspects - a redundancy approach has been applied maximising, where it was possible, the number of physical/functional redundancies, evaluating also the possibility to exploit synergies with the Lander configuration
- Programmatic and costs aspects - the AMALIA Rover has been designed taking into account the use of off-the-shelf items whenever feasible and maximising in house capabilities of the team members in order to reduce the procurement time and costs

Finally, the Google Lunar X PRIZE Mission requirements include the transmission back to Earth of defined datasets, called “Arrival Mooncast” and “Mission Complete Mooncast”. As described above, the two Mooncasts comprise a number of images and videos witnessing the arrival and exploration of the Moon surface. The requirements applicable to images and videos are briefly summarized in the following Table 3-1.

Panoramic Images	• Color image with minimum resolution of 0.3 milliradians/pixels • Horizontal Dimension 360° resulting in about 21000 pixels • Vertical Dimension 120° resulting in about 7000 pixels
Detail Images	• Color image with minimum resolution of 0.3 milliradians/pixels
Near Real time Video	• Color video of 30s minimum • 320x240 pixels resolution • 256Kbps bitrate • max 15fps resulting in a compression factor of about 40 (by assuming a color coding of 10bits/pixel)
High Definition video	• Color video • 1280 x 720 pixels resolution • max 15fps

Table 3-1 - Images and Videos Requirements

4.2. The AMALIA Rover Architecture

The AMALIA Rover has been designed in order to maximise the efficiency of the system, avoiding at the same time, when possible, the use of complex solutions.
The AMALIA Rover is substantially composed by a platform at which are attached:

- On the upper side a camera mast together with solar cells and radiators,
- On the lateral side two wings, accommodating additional solar cells and, finally,
- On the bottom part a Warm Electronics Box (WEB) accommodating all the AMALIA Rover electronics.

The wheels, together with their swing arms, are attached directly to the WEB lateral sides.
This architecture has been selected after several trade-off analyses performed at subsystem level.
One of the main issues faced during the initial study phase was the approach for the rover thermal control during the transfer phase from Earth to Moon. In fact, during the travel from Earth to Moon surface, the AMALIA Rover is inactive and it is accommodated on top of the AMALIA Lander. Due to its external accommodation, it will require to actively keep itself warm enough to prevent any damage. This can be performed in two ways:

- By using an active thermal control system with a microcontroller that continuously monitors all the temperatures trends and controls the switching on/off of the heaters of the AMALIA Rover main components, or
- By using a passive thermal control system, where dedicated Thermostats switch on/off the heaters to maintain the Rover units temperatures near a desired setpoint.

In this case, a simpler solution considering a passive thermal control system has been selected. For this reason, umbilical connections are provided between the AMALIA Rover and the AMALIA Lander, with the latter providing electrical power for the Thermostats controlled heaters ensuring the rover survival, and telemetry links for continuously monitor the rover overall status. The amount of electrical power required for thermal reasons by the Rover during the transfer is reduced by folding the two lateral wings on the upper side of the Rover platform. In fact, these wings provide thermal insulation by the Space environment because they are covered by MLI on their bottom side.
Another important trade-off analysis has been performed regarding the Telecommunications subsystem. Three were the proposed configurations under analysis:

- use of X-Band links to communicate with the AMALIA Lander and also directly with Earth;
- use of a L-Band link to communicate with the AMALIA Lander and the use of a X-Band link to communicate also directly with Earth;
- use of a redundant L-Band communication link to communicate only with the AMALIA Lander, with no direct communication link with Earth.

Also in this case, the simpler solution has been preferred and the last configuration has been selected. This solution has the minimum mass and it is less power demanding.
After the deployment onto the surface, performed by Lander, the Rover needs to be woken-up and checked before the umbilical and mechanical interfaces disconnection. Therefore, the AMALIA Rover will start a commissioning phase in which all the vital (Power, CDH, Video Acquisition and Processing System, Telecommunications) subsystems shall be initialized and their functioning calibrated and verified.
Only after the commissioning phase successful completion the AMALIA Rover will physically separate from the Lander and start to descend from the support plane.

4.3. The Rover Subsystems Design Approach

4.3.1. Structure, Mechanisms and Thermal Control

Structure Subsystem
The structure of the AMALIA Rover is based on a truss structure along the sides of the WEB. The WEB bottom panel accommodates the I/Fs with the Lander and with the Locomotion S/S. The WEB lateral sides protect the AMALIA Rover Electronics by the external environment. The Main Panel, located on top of the WEB, accommodates the AMALIA Rover Electronics. Two folded wing panels, accommodating the solar cells, are attached to it. The solar panels are deployed after the landing on Moon surface.
In order to keep low the mass of the AMALIA Rover, all the components of the structure subsystem are made in CFRP (Carbon Fiber Reinforced Plastic). The only exceptions are the Main Panel and WEB Bottom Panel: both of them have a honeycomb structure with the first one (the Main Panel – both the core and the skins) fully made in Aluminium alloy, while the second one (the WEB Bottom Panel) has the skins made in CFRP and the core in NOMEX.

Mechanisms Subsystem
The mechanisms subsystem of the AMALIA Rover includes the following components:

- a Mast on which are accommodated the navigation and acquisition cameras and the telecommunications antennas;
- the two foldable lateral Wing Panels.

The Mast control consists of 3 actuators (2 on the base and 1 on the top) that provide 3 degrees of freedom to the cameras, to guarantee the correct pointing for the acquisition of the images and of the videos:

- 1 degree of freedom around the vertical axis, in order to allow the acquisition of an horizontal

360° scan of the panorama

- 2 degrees of freedom around the horizontal axis, in order to allow a vertical 180° scan and to see directly in front of the wheels

The Mast is a 0.4m height boom, made in aluminium alloy, placed in the centre of the primary structure panel, providing the necessary height from the surface in order to have a free field of view. The motors have been selected from the Maxon RE025 series which has been used in NASA Phoenix program

- 1 Maxon RE025 (20.9 mNm maximum torque,<10 W) coupled with a gearhead (53:1 reduction ratio) and an encoder
- 2 Maxon RE025 (20.9 mNm maximum torque, <10 W) coupled with a gearhead (456:1 reduction ratio) and an encoder

The Wing Panels control consists of 4 deployment hinges (2 for each wing) that provide 1 degree of freedom to the wings, to guarantee (in folded configuration) thermal insulation to the AMALIA Rover radiators placed directly on top of the main panel.

The 1 degree of freedom is around the projection on the deployment hinge of the longitudinal axis of the AMALIA Rover. The necessary energy is stored within curved tape springs which are buckled and folded into stowed position. The deployment is triggered by release at the hold down points of the deployable appendage. New characteristics with respect to similar mechanisms are a complete guidance without friction pairs, combined with a high pointing stability achieved without additional latching elements.

Finally, mechanical non-explosive low shock retaining system (NEA actuators) are used to separate the wings from the main upper panel.

Thermal Control Subsystem

The goal of the thermal control subsystem (TCS) is to keep all the AMALIA Rover equipments within their operative and non operative temperature ranges (according to the mission scenario) on Moon surface and during the transfer orbit from Earth to Moon, providing suitable hardware and concepts for managing the internally dissipated heat, and coping with the environmental heat loads and the radiative environment.

The major parameters that influence the TCS design and development are:

- Thermal requirements of the items accommodated on the AMALIA Rover
- Thermal environment during the trip from Earth to Moon
- Thermal environment on Moon surface
- Total amount of power dissipated by the AMALIA Rover in its different operative modes
- The distribution of the thermal dissipation inside the AMALIA Rover
- Configuration and interactions with other subsystems

Therefore, the first step was to determine the allowed temperature ranges, both in the operational and non-operational phases, of all the AMALIA Rover components, in order to highlight the most critical ones for the thermal control point of view. The table below shows a preliminary estimation of the thermal requirements of all the components accommodated on the AMALIA Rover:

Component	Design Operational Temper. Range [°C]	Design Non-Operational Temper. Range [°C]
Structures	-150/150	/
• Mechanisms, internally mounted	-20/60	-30/70
• Mechanisms, externally mounted	-10/50	-100/100
Batteries	0/30	-10/40
Power Conditioning and Distribution Unit	-20/60	-30/70
Cameras	-20/60	-30/70
Avionics, Computers	-20/60	-30/70
Mass Memory	-20/60	-30/70
Telecommunications	-20/60	-30/70

Table 3-2 - Thermal Requirements

As it is shown in Table 3-2, the batteries represent the most critical component from the admissible temperature ranges point of view.

Once the most critical component has been identified, the two design cases (Hot Case and Cold Case) have been defined.

As Hot Case has been considered the period during which the AMALIA Rover is moving on lunar surface. In fact, in this case, the lunar surface temperature reaches the maximum value of 400K when the sun is at the zenith on the Moon Equator. A solution using radiators have been chosen as baseline in order to reject heat loads coming from the internal components equipments during lunar surface operations. The AMALIA Rover body is also fully covered by MLI in order to insulate it from the hot lunar surface.

Instead, the Cold Case is represented by the trip from Earth to Moon. During this transfer, the AMALIA Rover is accommodated on top of the AMALIA Lander that has to provide to the Rover heaters the required amount of electrical power to keep the temperatures of Rover components within their non-operational limits. Two configurations have been analysed for this case (see Figure 3-3): one for which the AMALIA Rover is in shadow with respect the Sun-light, and one for which it is heated by the Sun-light. While in the second case no electrical power is required from the heaters, in the first case the AMALIA Rover needs to be heated to survive.

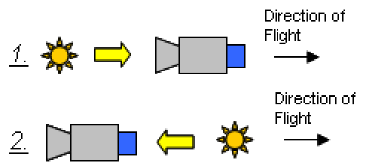

Figure 3-3 - Cold Case Configurations

The MLI still allows to insulate the Rover body from the external extreme environment and, in order to mask off the radiators during this phase, the lateral wings are folded on them, reducing the heat rejection.

4.3.2. Locomotion

The locomotion subsystem is based on four non-pneumatic elastic wheels driven directly by brushless torque motors located in the hubs. The wheels are connected to the body via four independent longitudinal swing arm suspensions, provided with a torsional spring but no damper. Each of the four units made by the wheel, its motor and its suspension constitute an independent corner, which can be easily assembled on the rover chassis (Figure 3-4). The four corners are identical except for some parts which may be made in two distinct versions, a right-hand and a left-hand one. Each corner has a mechanical, an electric and, possibly, a pneumatic interface. The latter is used to supply a low pressure gas filling the internal cavity, in such a way to prevent lunar dust to enter the inside of the unit. The need of pressurizing the internal of the wheels will be assessed during the tests to be performed on the engineering model at present at the design stage.

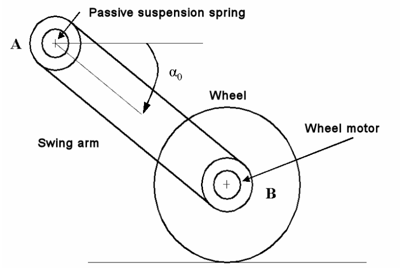

Figure 3-4 - Sketch of one of the corners

The locomotion subsystem is currently designed for a nominal mass of the rover of 30 kg in lunar conditions. However, the system can be used, with reduced performances, also for tests in Earth conditions, provided that two elements (the elastic tire and the suspension spring) are substituted with more rigid elements.

The following performance was assumed:

- Max. speed on level ground: 50m/h= 0.014m/s
- Max. grade: 36% (grade angle ≈ 20°)

The configuration chosen for the wheel is an all-metal elastic wheel of innovative design [R1, R2].

Following the analysis in [R2] based on a three-dimensional, fully nonlinear FEM model made of 18036 quadrilateral shell elements with 4 nodes and 5 integration points in their thickness, a displacement of about 6 mm in operating conditions was obtained. The force-displacements curves obtained for the two conditions of load on a single spoke and load in between two spokes are shown in Figure 3-5. The two curves are almost completely superimposed, except for the highest values of the load, showing a smooth working of the structure.

The wheel for the engineering model can be obtained by just increasing the thickness of the rim and the spokes (0.4 mm instead of 0.2 mm), obtaining the curves shown in Fig. 1b.

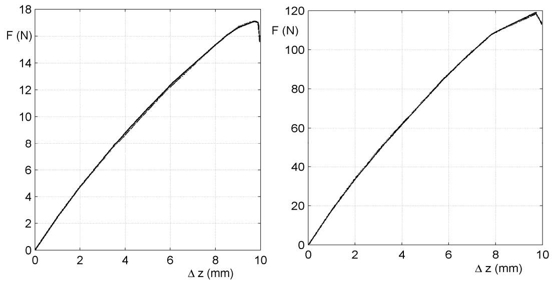

Figure 3-5 - Force-displacement characteristics of the wheel for the actual rover on the Moon, a) and the engineering model (Earth conditions, b) obtained from the nonlinear FEM model.

The maximum equivalent stress (Von Mises criterion) at the nominal displacement of 6 mm is 404 MN/m^2. This value is possibly an overestimate, since it occurs in a very small zone at the hub-spoke interface. A finer mesh needs to be used for more accurate results. A travel limiter can be set to prevent displacements larger than 8 mm, so that a maximum stress of about 520 MN/m^2 is reached.

The maximum stress for the engineering model (Earth conditions) at the nominal displacement of 5 mm is 680 MN/m^2. Since the wheel for Earth gravity is expected to be used for a reduced time and with reduced loads, this design can be accepted.

These wheels need still to be tested on the engineering model.

Since all wheels are driving, a wheel with a diameter of 180 mm allows to manage an obstacle of about 70 mm height and to traverse a crevice of about 120 mm, values that may however be reduced by the low traction available on regolith. The contact area under nominal load in lunar conditions can be estimated as 45 cm2, yielding an average pressure on the ground of 2700 Pa. This value of the contact area is obtained from purely geometrical reasoning and hence is a lower bound. The estimate of the pressure is thus an upper bound, that anyway guarantees no or very little sinkage.

Assuming a conservative value of the rolling resistance coefficient when travelling at top speed on regolth f_0 = 0.1, the total resistance to motion at low speed, the torque and the power required for motion at each wheel are

R = 1.22 N,   T = 0.11 Nm,   W = 0.0170 W .

On a 20° slope the power and the torque are

W = 0.0742 W,   T = 0.477 Nm .

Custom built brushless torque motors were chosen. Their main characteristics are:

Winding Resistance	4,9 Ω
Torque Constant	0,52 Nm/A
Nominal Current	1,4
Peak Current	2,8
Nominal Torque (dT 50°C)	0,66
Peak Torque	1,29

The total power needed for moving on level ground (including the losses in the motor drivers) is 1.15 W for the whole rover. The power increases to about 19 W to manage a slope of 36%; even in these conditions the motors and the power amplifiers have still a large reserve power.

On Earth, the values of the total power increase to 3.51 W on level ground and 103 W on a slope of 14%, keeping into account a decrease of the rolling resistance on a purposely built test surface), which can be reduced by performing the tests not at full load. They are anyway acceptable for short duration tests, particularly because on Earth it is possible to provide adequate cooling.

Longitudinal swing arms suspensions were chosen. Owing to the very low speed, there is no need for dampers, and no attempt to use active suspensions was done. The elastic elements are small steel torque rods, whose stiffness was computed in such a way to guarantee a fairly even load distribution on the ground even on rough terrain.

A mathematical model to study the static equilibrium conditions on uneven ground yielded the results reported in Figure 3-6: assuming that one of the wheels (in the figure the front right wheel) is on an obstacle of a given height, while the others are on a flat surface, the forces on the ground were computed. The computation was performed assuming that the wheels are stiff, which is quite a conservative assumption. On an obstacle of 100 mm the forces on the ground are still fairly well distributed on the wheels: 9.59, 13.34, 9.21 and 16.46 N on the front left, front right, rear right and rear left wheels respectively.

The liftoff of one wheel from the ground occurs only on an obstacle higher than 230 mm.

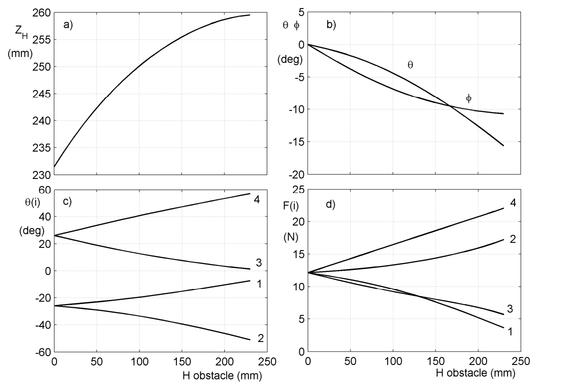

Figure 3-6 - Configuration of the rover while standing with one wheel on an obstacle. a): vertical position of the body; b) roll and pitch angles, c) angles of the suspensions; d): forces on the ground. The order of the wheels is front left, front right, rear right and rear left.

The springs designed to be used on the Moon cannot be used on the engineering model during tests on Earth. The suspensions of the engineering model are identical to those of the actual rover, with just a different set of springs

A preliminary mass budget of the locomotion subsystem (wheels, motors, suspensions, power electronics plus 20% allowance) yielded 1700 g for each corner. The total mass of the mobility system can thus be evaluated at about 6.8 kg. The mobility system constitutes less than 23% of the mass of a 30 kg rover.

4.3.3. Power

The power system consists of a regulated bus at 12 V, supplied by a photovoltaic (PV) system based on triple-junction solar cells as a primary source and a Li-Ion battery as a secondary source.

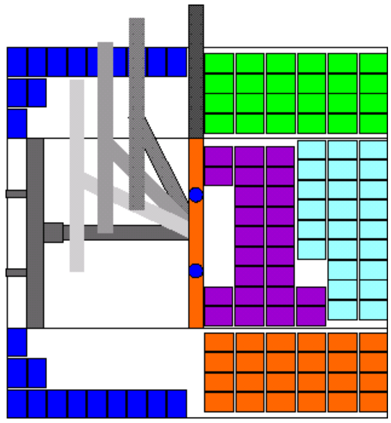

Figure 3-7 - Solar array geometry: the five strings are evidenced in different colours. It can be observed that at maximum two solar cells in the same string can be interested by the shadow of the Mast.

The solar system comprises two deployable panels and a fixed panel sharing the top surface of the rover with thermal radiators. The design of the solar array and of the related power conversion unit was heavily influenced by the attempt of minimizing the effects of the annoying shadows projected on the solar array by the boom of the image sensors. The geometry depicted in

Figure *3-7* minimizes the number of shadowed solar cells. On the other hand, this asymmetrical arrangement imposes requirements to the vision and locomotion subsystems, which is designed to allow exchanging stem with stern at noon, in order to keep the shadows on the radiator side.

From an electrical point of view, the shadowing effects can be faced by providing a specific buck dc-dc converter for every string of the solar array, as shown in

Figure 3-8. This way, the operating voltages of different sections are independently set on the basis of the number of illuminated solar cells and of their temperature. The Array Power Regulators (APR) will be provided with Maximum Power Point Tracking (MPPT) capability, in order to minimize the battery Depth Of Discharge (DOD) and charging time. Other conversion approaches well-known for their low weight and high reliability like the Sequential Shunt Switching Regulator (S3R) have been discarded, as their efficiency would be extremely reduced when operating with a low-voltage bus and a highly variable solar array.

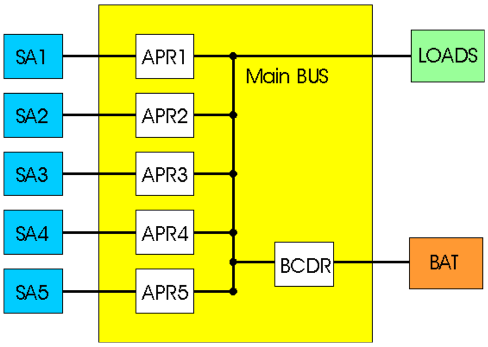

Figure 3-8 - Outline of the power system

The battery will be mostly required to provide short current pulses, intended to sustain the bus voltage during load peaks, or to supply the rover during short eclipses when passing behind the Lander or other small obstacles. Therefore, the main design driver was not energy, but peak power.
On the other hand, the most interesting technology for application in rovers is Li-Ion, providing extremely small and lightweight batteries, with a small self-discharge. Unfortunately, excluding very particular devices intended for specific use in launchers, their typical power density (120 W/kg) is not so interesting as the energy density (larger than 120 Wh/kg). This feature heavily affects the power system design: full power to the bus (100 W) can be only obtained by a battery providing one hour of autonomy under full load, which is by far exceeding the mission requirements. With reference to the product catalogue of SAFT, the same performance can be obtained by using a 5S1P battery of MPS cells, with a 750 g mass (only cells) and a nominal voltage of 18V. An alternate solution is to use larger cells, like the VES 100, in configuration 1S1P, with a nominal voltage of 3.6V: the mass would be slightly increased (810 g), but the harness would be extremely simplified. On the other hand, both solutions require a Battery Discharge Regulator (BDR), impeding the simplest approach of a semi-regulated bus to be used for the power system.

4.3.4. <u>Telecommunications</u>

This subsystem is very important in order to successfully accomplish the Google Lunar X-Prize mission requirements. In fact, as explained in chapter 2, the AMALIA Rover must send/transmit back to Earth a set of data packages required by the X Prize Foundation (XPF), including the two MoonCasts. As it will be explained later, the size of these data packages has a large impact on the design of this subsystem because it affects the overall mission duration.
Therefore, the Telecommunications subsystem includes a transmission/reception system to manage the communications with a relay system (the AMALIA Lander) that allows the link with the Ground Control Centre, mainly in terms of reception of the telecommands and transmission of the telemetry data and of the above mentioned XPF data packages. This subsystem provides also umbilical interfaces to the Ground Support Equipment and to the AMALIA Lander in order to be tested on Earth and checked up to the deployment on lunar surface. As above explained the AMALIA Rover Telecommunications S/S architecture foresees the usage of the AMALIA Lander as data relay with Earth both for high throughput data (images) and low rate data (TM/TC) for rover monitoring / control.
As explained in chapter 4.2, the chosen configuration is the following:

- 2 Low gain omni-directional (L-Band) antennas (1 main and 1 redundant, data rate 1Mbit/s) with the AMALIA Lander
- 2 L-Band transponders (1 main and 1 redundant)

This configuration is shown in Figure 3-9.

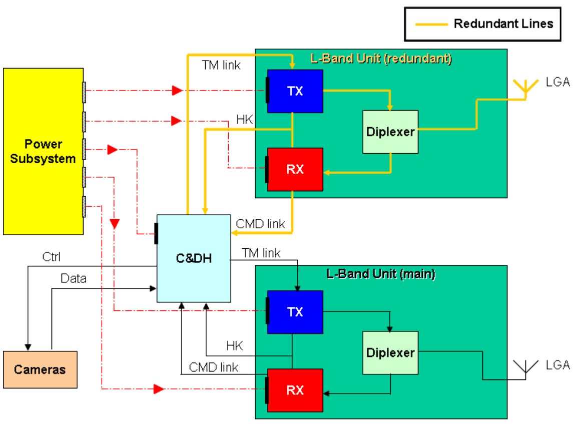

Figure 3-9 - Telecommunications Subsystem Configuration

The above figure shows also the redundancy links.
This configuration does not allow communicating directly with the Ground Control Centre, but only with the AMALIA Lander. The L-Band has been chosen because it requires a limited amount of electrical power with respect the other communication bands, made

possible by the short distance between the AMALIA Rover and the AMALIA Lander. In fact, the maximum foreseen distance between the two elements on lunar surface, in the nominal mission, is of 500m. At this distance the L-Band results more efficient than others.
The chosen data rate is of 1Mbit/s, and this is due to the following reasons:

- the AMALIA Rover GNC autonomy level. As it will be shown below, the AMALIA Rover foresees two main GNC autonomy levels: Teleoperated Drive and Autonomous Drive. In the case of Teleoperated Drive, the AMALIA Rover requires a Streaming video in real time during movement. This implies a requirement on the data rate that shall be at least 210kbps to guarantee the transmission from the Moon;
- the overall mission duration. The available time to perform the overall mission (transmission of the GLXP required data set and movement of 500m on lunar surface) is very short due to the inclination of the solar rays at the chosen landing location (Moon Equator - maximum lunar daylight of 14 terrestrial days), that reduces the amount of available solar power, and to the fact that the AMALIA Rover is not currently designed to survive to the long lunar night (14 terrestrial days). Therefore, in order to be able to accomplish in less than one lunar day the mission, transmit the huge amount of data required by the X-Prize Foundation and perform the 500m of movement, a high data rate is required.

4.3.5. GNC

In order to choose the Rover GNC concept, it is obviously important to take into account the key characteristics/peculiarities of the overall AMALIA mission. The design of the Rover GNC will therefore have to be able to both operate safely in a wide range of conditions (e.g. taking into account the various environment uncertainties), and also to allow quite high velocities, in order to complete the mission in the limited time available. As described above, there are two autonomy levels available - the Teleoperated Drive and the Autonomous Drive. In a first approximation, it can be said that in the first case, the rover is commanded directly from Earth, while in the second, there are periods when the rover moves autonomously. It is important to take into account the fact that in both cases the key GNC functions to be realized by software are the same - but the place when these are realized (Moon or Earth-for operator support), and also their level of complexity, can change. The key GNC functions are the following:
- **Image Acquisition from Cameras and Stereo processing** - this is the basic function that allows the acquisition of the images and their initial processing for estimating depth
- **Environment and State Estimation** - the objective of this function is to reconstruct the terrain around the vehicle, and also the state of the vehicle itself, using the available sensors
- **Guidance & Control** - by taking into account the state and terrain estimates, this function allows the processing of the map and the generation of a "safe" path, and also its realization through the commanding of the wheel motors.

The first function is done on the rover (on the VAPS electronics) for both the autonomy levels, while the other two are done on the rover only for the Autonomous Drive mode. These two functions can be further split in a number of sub-functions; the resulting scheme is shown on the Figure 3-10

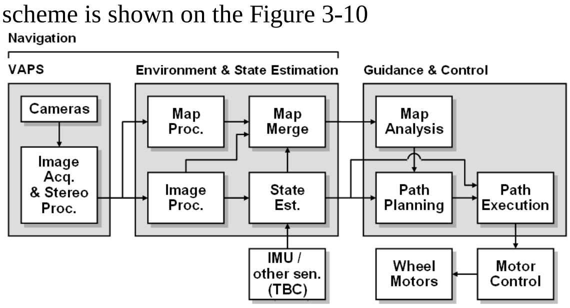

Figure 3-10 - Rover GNC Block Diagram

The key features of these sub-functions are the following:
- **Image Acquisition and Stereo Processing**: here after the acquisition of the left and right camera images, these two are compared in order to obtain a 3D reconstruction of the terrain that can be seen by both the cameras. Intuitively, by determining the apparent motion of the observed points when passing from one image to another, it is possible to estimate (by triangulation) the position of these points. These positions are expressed in a reference frame that is fixed w.r.t. the two cameras
- **Map Processing**: this sub-function performs a refinement of the resulting 3D reconstruction in order to obtain a "Local Map" of the terrain that can be then easily included in the "Global Map", in the "Map Merge" sub-function
- **Image Processing**: the objective of this sub-function is to compare images taken at different times by the same camera, in order to obtain an estimate of the relative translation and rotation between two image acquisition positions
- **State Estimation**: here the vehicle state (in terms of position and attitude) in an "absolute" reference frame is estimated by merging the relative translation and rotation data with the measurements obtained from the Inertial Measurement Unit during the movements (and also other sensors, if available)
- **Map Merge**: this sub-function is used for generating (and updating) a "Global Map" storing the elevations

and features of the observed terrain in an "absolute" reference frame; each time a new "Local Map" is available, it gets "merged" to the previous version of the "Global Map"

- **Map Analysis**: the Global Map is analyzed by visual processing to identify the obstacles and the shape of the surface. The result is an Obstacle Map that consists of a 2D array of cells. Each cell of the map represents one of the following situations: traversable, no-traversable and potential hazard. The Elevation Map, obtained by the 3D reconstruction of the terrain, is merged with the Obstacle Map to yield a Road Map. Finally, to each cell of the Road Map a suitable cost is assigned.

- **Path Planning**: the path is planned by computing the relative costs of moving from any particular section of space to any of the adjoining sections. The process is repeated until a desired destination is encountered. The path is broken into segments that correspond to straight lines and turns. Finally, a set of candidate paths is identified.

Once the minimum cost path is selected, the planner identifies landmarks where the rover is expecting a bump from a particular rock and the segments around the landmarks are broken into smaller ones.

The curved segments are constant curvature and therefore all segments can be uniquely defined by the rover's current position and orientation, the destination point and the direction of travel. As a consequence, the navigation data can be predicted and compared in the path execution phase with the actual navigation data.

- **Path Execution**: this sub-function has the tasks of path-tracking, steering control and obstacle avoidance.

Models of the interaction with the lunar soil can be used to predict the rover's behaviour along the selected path [R3]. This can help the rover's pilot in the steering control.

In the Teleoperated-Drive Mode, all the tasks are in charge of the operator at the ground control centre.

The path and the current position and orientation of the rover can be suitably displayed at the control centre. The aim of the operator is to track the nominal path.

In the Autonomous-Drive Mode the tasks are executed by the rover on-board computer.

The autonomous steering control system has to be able to effectively track the given path, by minimizing the errors in both the lateral displacement and orientation of the rover relative to the planned path.

The displacement error is defined as the distance from the centre-point of the rover to the closest local point on the planned path. The orientation error is defined as the angular difference between the rover orientation, θ, and the slope of the tangent to the local planned path θ_P. The control of the steering angle $\alpha = \theta - \theta_P$ is achieved by the slipping of the four-drive wheels. The model of the slip has to be taken into account to correctly devise the model of the controlled dynamics [R4].

If the rover encounters an unplanned obstacle during its travel, it would have no choice but to stop, notify the navigator, and wait for a new path plan. For large scale obstacles and terrain features, say larger than the rover, this may be the best action, since the rover has made an unexpected encounter, and the resources and abilities of the longer-range navigation systems should be consulted before "driving" around the obstacle.

For a small obstacle, say less than the size of the rover, but greater than that which can be easily overcome or cleared, the rover might be more expedient to modify the target trajectory to avoid the obstacle. The application of the Artificial Potential Field (APF) around the position of the obstacle facilitates the rover guidance.

The APF introduces a type of non-contact force control, as repulsive electrostatic forces [R5], where the sum of the repulsive force fields is transformed into an acceleration command to the control system.

4.3.6. <u>Command and Data Handling</u>

The Command and Data Handling (CDH) Subsystem has the main task to execute all the computation functionalities, coordinate/control the activities required for the operations of the AMALIA Rover, and also realize the necessary redundancy that allows the correct functioning even in case one of the board fails. It provides also the interfaces with all the other subsystems, allowing to manage the housekeeping data to be provided to the telecommunications subsystem and the telecommands received by the Ground Control Centre. Umbilical interfaces with the AMALIA Lander and the Ground Support Equipment are included.

In some specific cases (e.g. the locomotion subsystem) the control of some Subsystems parts is not directly performed by the CDH, but it is demanded to dedicated electronics within these S/Ss, leaving to CDH the management of housekeeping data, the commands issue, the monitoring, supervision and interfaces functions. For instance, robotics mechanisms need a specific electronic device to convert the commands received by the CDH to drive the actuators, as well as the video acquisition devices require a dedicated Video Acquisition and Processing System, as described in chapter 4.3.7 . In particular, the Command and Data Handling Subsystem includes the following boards:

- 2 Processor boards (1 main, 1 redundant)
  - processor, >= 20 MIPS
  - local program & data memory
  - control / monitor of the operation of the Rover subsystems and anomalies detection
  - Rover GNC algorithms implementation according to the selected operational modes
- 2 I/Fs boards (1 main, 1 redundant). They provide:
  - at least 3 SpaceWire I/Fs as minimum with the other CDH's components and with the other S/Ss (2 with the two TMTC boards, 1

with the VAPS electronics)

- at least 5 RS-422 I/Fs as minimum with the other CDH's components and with the other S/Ss (2 with the two Motion Control Boards, 1 with the IMU, 1 with the PCDU and 1 with the Locomotion Electronics Module)

- 4 DC/DC Modules (2 main, 2 redundant)
  - provide power supply to the other C&DH boards
- 2 TM/TC I/F & reconfiguration board (1 main, 1 redundant)
  - manage the interface with the Telecommunications subsystem (using a serial link)
  - provide Watch-dog functionality
- 2 Motion Control boards
  - drive and monitor all the motors of the Mast
  - 2 brushless motors drivers on each board
  - separated accommodation (one for each board) of the two pan motors (1 main, 1 redundant) of the Mast in order to keep safe their functionality

In the Figure 3-11, the Command and Data Handling interfaces with other subsystems/elements are shown.

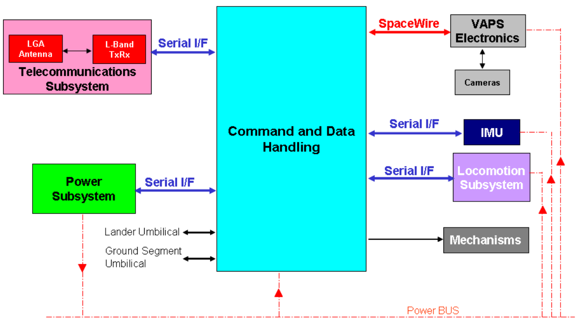

Figure 3-11 - Command and Data Handling Interfaces

4.3.7. <u>Video Acquisition and Processing</u>

The images and video requirements mentioned above (chapter 4.1) are fulfilled by the Video Acquisition and Processing Subsystem (VAPS). The VAPS, in addition to the acquisition of still images and video, as defined by the *Mooncasts requirements*, supports the GNC SS by processing in real time the acquired images by dedicated algorithms having, as main purpose, the 3D reconstruction of the lunar surface.

The Video Acquisition and Processing Subsystem is composed of two main components:

1) The Camera System Optical Head (CSOH) comprising three cameras integrated in one housing, the optics, and the baffles
2) The Camera System Electronic Module (CSEM) that handles the image acquisition, storage, compression and transmission functions

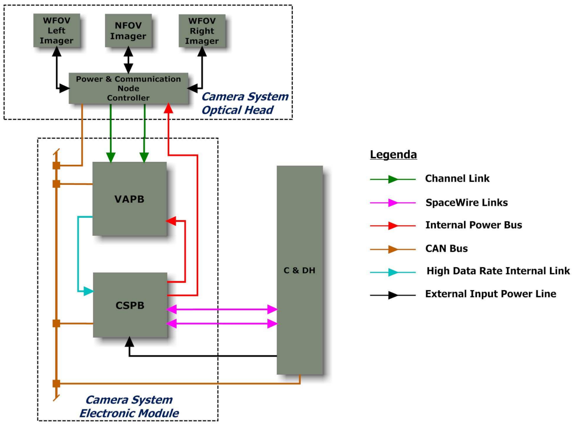

Figure 3-12 - VAPS functional diagram

Both the CSOH and the CSEM are based on consolidated architectures already employed by TSD in other space applications (on board Satellites, ISS, and Sounding Rockets).

The design guidelines that lead to the definition of the CSOH and CSEM architecture are:

- FPGA based design to increase performances and integration level
- High reliability achieved by adopting optimized redundancy techniques that allow to minimize mass and volume
- Intelligent Power management to reduce power consumption without impacting on the overall performances

The design of the CSOH and CSEM takes advantages from the latest methodology in the fields of high-throughput data transfer, high-speed digital design and printed-circuit board manufacturing in order to achieve high performances and very compact sizes.

Almost all the adopted components are available in rad-tolerant version.

Figure 3-13 shows the data flows inside CSOH and CSEM and their I/Fs and also the redundancies implemented in the subsystem.

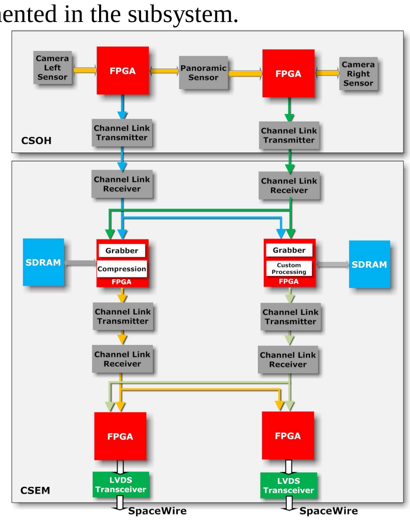

Figure 3-13 - Data flows inside CSOH and CSEM

The adoption of two identical FPGAs for each stage (image sensors proximity electronics, acquisition & processing, and control & communication) and redundant and cross-strapped resources for the input/output I/Fs, guarantees a single fault tolerance for the main functions, and a partial tolerance for some other functions (in some fault cases the function is ensured but with a degradation of the performances).
Three cameras of the CSOH adopt the same sensor that was selected by considering, as candidates, sensors based on CMOS technology and offering native resolution equal to the one requested by GLXP (720p) and to the higher HD resolution standard (1080p), thus allowing the transmission to Earth of images with a quality also better than the requested one. The only difference is in the optics; two of them work with wide field of view (WFOV) and one with narrow field of view (NFOV).
The table 3-3 and the figure 3-13 present respectively the CSOH main specifications and the mechanical configuration.

Imagers	Three CMOS Active Pixel sensor
Image size	Up to 1920 x 1080 pixel (each)
Frame rate	Up to 15fps @ full resolution
Supply [V]	9 to 18 Vdc
Digital video output	Two LVDS high-speed serial links (Channel link)
Configuration & status I/F	CAN Bus
Power	~ 4W
Mass	~ 0.65 [Kg]

Table 3-3 - CSOH main specifications

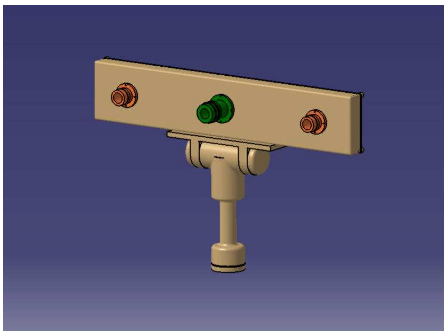

Figure 3-14 - CSOH mechanical configuration

The CSEM is based on only two boards:

- the Video Acquisition and Processing Board (VAPB) for image grabbing, Wavelet compression, and 3D image reconstruction
- the Communication, Storage and Power Board (CSPB) for data communication and storage, and CSEM control/powering

The following Table 3-4 summarizes the main specifications for the CSEM.

Video Inputs capability	30 Mpixel/s allocated on 3 independent video channels
Pixel size	8 to 12 bit per pixel
Image buffers	Up to 4 Megapixels (one channel 1920x1080 + two channels 1280x720)
Frame Rate	One 2Mpixel channel @ 15fps or two 1Mpixel channel @ 15fps
Digital Output	2 SpaceWire I/Fs running (each) up to 40Mbit/s
Compression	7.5 Mpixel/s in loss-less mode and up to 30 Mpixel/s in lossy mode
Compression factor	From 1 to 60
Storage	Volatile on-board data storage up to 8 Gbit
Voltage	9 to 18 [Vdc]
Power	~4 [W] in idle or download mode ~8.5[W] in acquisition or acquisition and download mode
Mass	~1.2 [Kg]

Table 3-4 - CSEM main specifications

The Table 3-5 reports the performances of the VAPS versus the specific GLXP mission requirements.

Operative modes	**GLXP Requirements**	**Proposed Camera System Performances**
High definition video	Colour video 720p (1280x720 pixels) @ 15[fps]	Colour video up to 1080p (1920x1080 pixels) @ 15 [fps]
Near Real Time video	30[s] of colour video with 320x240 pixels @ 15 [fps]	Continuous Real Time Transmission of Colour video up to 640x360 pixel @ 15[fps] with ~28 compression factor resulting in 1[Mbit/s]
Detail Images	Colour image with minimum resolution of 0.3 milliradians/pixel	High-definition images with 1920x1080 pixel @ 0.3 milliradians/pixel
Panoramic Images	Colour images with minimum resolution of 0.3milliradians/pixel 360° H → 21000 pixels 120° V → 7000 pixels	Panoramic Images composed of 77 (11x7) 1080p images @ 0.3 milliradians/pixel
Stereo Video Images	N.A.	360[s] of colour stereo images up to 1280x720 pixels @ 15[fps] with ~10 compression factor resulting in 8 [Gbit]

Table 3-5 - VAPS performances vs. GLXP mission requirements

4.4. The Rover Operations

The main schedule of the operations of the AMALIA Rover includes the following phases:

- **Initial Operations**
- **Surface Operations**

The **Initial Operations** are the ones already described in chapter 4.2 and they include the **Transfer Phase** and the **Commissioning Phase**.

Instead, the **Surface Operations** include a set of Main Tasks that have to be performed on lunar surface when the mission starts, and they are related to:

- Activities dedicated to:
  - transmit and receive XPF data packages
  - transmit MoonCast data packages
- Movement on the lunar surface

This set of Main Tasks has been scheduled in order to obtain a complete mission profile of the AMALIA Rover. The overall mission schedule depends on the choice about the level of autonomy. Currently, two levels of autonomy have been foreseen:

- Teleoperated Drive
- Autonomous Drive

The **Teleoperated Drive** is a direct command from an operator on Earth. As said in chapter 4.3.4, this “Drive” requires a high data rate for streaming video in real time in order to allow operator to see, almost in real time, what is the terrain in front of the Rover and to choose the best direction to move. The minimum data rate required could be obtained considering, for example, the video codec H.263. This codec has been developed for Video coding for low bit rate communication. The considered data rate is 210kbps with a framerate of 15 frames/sec.

The **Autonomous Drive** is performed only when the Earth-Moon link data rate is reduced. In this case, the Rover can autonomously move on lunar surface and the operator has only to provide the direction after each 5m performed.

For each level of autonomy, the main tasks have been subdivided in a set of sequences of activities. These sequences are repeated during the overall mission.

While the **Activities** are a set of videos/images and specific XPF data that have to be transmitted/received from the Moon surface at the beginning and at the end of the mission, the **Movement** to perform 500m on the lunar surface is a more complex Task that has been subdivided in steps, each one of 5m of length. For each step, a set of sequences of sub-activities is repeated. These sequences can change depending on the different level of autonomy and on the travelled distance. The list of sequences of sub-activities is the following:

- **Full Panorama Collection** (360° panorama images acquired only once at the **beginning** of the Surface Operations);
- **Navigation Panorama Collection** (120° panorama images acquired **after each 5m** of movement, except when Travel Panorama is taken);
- **Travel Panorama Collection** (240° panorama images acquired **after each 100m** of movement);
- **Navigation** (movement of 5m)

Repeating these sub-activities in a suitable set of sequences, the overall AMALIA Rover mission is scheduled.

In the definition of the schedule of the AMALIA Rover, it is also important to verify the link with the Ground Control Centre and, then, the availability of the Ground Stations (GSs) that will support its mission on lunar surface. Depending on this availability, the overall mission will be shorter or longer.

The Ground Station System represents the direct interface with the space segment. During the Low and Early Orbit Phase (LEOP), a support is expected from the organization in charge of the launch, and conventional Italian satellite stations could be used. During Moon transfer phase and, mainly, surfaces’ operations, antennas have to provide long distance and high rate connections; these requirements make 15 meters class antennas necessary. The main infrastructure during surface operations will be an Italian Ground Station located around 45°N or 42°N and designed to manage the whole data transfer and totally dedicated to the AMALIA Mission. The utilization of an additional support ground station will be taken into account depending on the operational needs (e.g. on-board rover autonomy). In case a second Ground Station is necessary to provide a wider coverage of the landing site, it will be chosen at an appropriate longitude in order to provide complementary connection periods. Being the Moon orbit inclination w.r.t. the Earth’s equator between 18° and 28°, the ground station latitude that provides the maximum connection period depends on the launch date. Thus, to increase the versatility and coverage of the network, the preferable location of a second station is at moderate latitudes near the equator.

In the case of the Teleoperated Drive, ground operations will be in charge of DEM (Digital Elevation Model) generation and obstacles avoidance. The Mission Control System (MCS) will be designed to meet such needs. It will be equipped with powerful processing tools able to compute the DEM of the terrain surrounding AMALIA rover. The rover images and DEMs will be compared with the ones obtained by past satellite missions and collected into a dedicated database at ground to be included also into the trajectory computation. Another MCS important feature will be the rover simulator necessary to predict power and thermal subsystems behaviour as well as the illumination conditions, important for ground image processing operations.

Finally, the Ground Communication Subnet interconnects all operational ground facilities, in particular between MCS and ground stations. It won't be created an ad hoc network to support the operations, but it will be used a qualified Net already fully functional, reducing costs and development time.

5. REFERENCES

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