ANALYSIS AND DESIGN OF MICROROVER DELIVERY SYSTEM

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ABSTRACT

Recently small, mobile surface elements have been considered as interesting payloads to be sent to bodies of the Solar System due to the advantages that they offer with respect to traditional missions; mainly mass reduction. Moreover several excellent designs already exist and are well developed such as Nanokhod rover developed by vHS; a 2kg tracked and tethered system suitable for use in a wide variety of locations. Owing to limited dimensions; rovers are not autonomous in terms of power and communication. This leads to a tethered concept where a lander provides communication and power to microrovers; which is a trade-off between autonomy and lifetime.

Nevertheless there is no full mission concept developed for this attractive payload, wherefore this report presents a preliminary system design for a mission to safely deliver microrovers to Mars surface and provide them the required support to allow their operation in Martian land. In order to assure these objectives top-level budgets of the lander, that supplies payload during surface phase, and the delivery module, which has the responsibility to decelerate Rover System in the EDL phase, are introduced.

1. INTRODUCTION

Not only microrovers are well developed for a range of target bodies but also they have been considered as interesting payloads to send to surface bodies of the Solar System because they offer advantages with respect to traditional missions. Nevertheless there is no full mission concept developed for this attractive payload, wherefore this report presents a study to find the most interesting scenario for this kind of mission and then preliminary system design for a mission to deliver microrover to Mars surface and provide them the required support to allow their operation in Martian land.

From the last sentence two main objectives are extracted for such a mission: the delivery of microrovers, provided by a Delivery Module, and the support of their activities on the surface, provided by a lander.

Owing to limited dimensions of microrovers they are not autonomous in terms of power and communications, so it leads to a tethered concept where lander provides it to them. This concept entails advantages, such as lifetime is increased, and disadvantages, in particular the limited autonomy of microrovers.

Delivery Module has the responsibility to decelerate Rover System (lander and microrovers) from orbital velocity to nearly 0 relative velocity to assure a safe landing. It should be emphasized that this phase is extremely hazardous because it takes place in an atmosphere whose conditions are difficult to predict and it involves a large energy change.

2. BENEFITS OF THIS MISSION

The main attraction to research into microrover missions is that they can obtain similar objectives than traditional mission with reduced mass, complexity and cost. To achieve this goal microrovers have been developed as the most suitable payload. However, up to now no complete microrover missions have been developed.

1.1 Expansion of Space Programs

Up to now just few planetary surface missions have been carried out. The main reasons of this low number are the lack of technical resources and funding that are needed to perform these missions, and the high complexity mixed with an unknown environment at arrival. However, the type of mission that this study deals with needs smaller budget to be launched. Therefore, if the devoted budget to these missions remains equal, more missions can be carried out, introducing a higher variety in space programs and increasing the achieved milestones. So it can be concluded that this concept of mission introduce benefits to space programs.

1.2 Benefits in risk/cost ratio

Interplanetary missions entail more risk than Earth missions because they travel into unknown environments and sometimes their conditions are difficult to predict.

If a traditional mission developed with a huge budget goes into the target body and fails, there is a lot of wasted funding. However, if the same budget is devoted to promote multiple microrover missions, due to probability, it is more possible that at least one of them survives. As a conclusion, in terms of risk it is better to use the budget in several small missions than to use it in just a big one.

1.3 Demonopolization of Space Agencies

The most frequent problem that space agencies confront is restricted budgets. This problem is even more important to small agencies. That is why their interventions are much reduced and their activities are directly dependent upon bigger agencies which profit of this cooperation. Introducing this kind of low cost mission enables the autonomy of space agencies that have not had any prominence until now.

Moreover, as it will be explained in the next section, this mission has been thought to travel to Mars because microrover missions can play an important role in this destination at present. Due to there are plans to send manned mission to Mars it implies that a perfect knowledge of the planet should be reached before it will happen. Microrover missions become very useful because they enable to send more reconnaissance missions with different objectives than a traditional mission that will cost the same but its risk is higher. Large systems will usually have a role for in-situ analysis (e.g. Mars Science Lab due to be launched in 2011), but microrover missions can add considerable value, and distribute the science between mission types, and between different locations on the surfaces, which results in much better quality of exploration.

3. EXPLORATION SCENARIOS

Due to present development of microrovers, they are wining attraction to be carried as payload in space missions. Therefore there is a wide variety of possible scenarios where this kind of payload can be included.
In order to define these possible scenarios, it is needed to define 3 main parameters: number of microrovers, mission proposal and destination.

3.1 Number of microrovers

Payload of the mission can be just a single microrover (*single* configuration) or a group of them (*multiple* configuration).

3.2 Mission Proposal

Referring to mission proposal it is possible to differentiate between *dedicated* missions where microrovers are the only payload or *piggyback* which defines a mission that adds microrovers to the main payload.

3.3 Destination

Whereas the other parameters offer just a couple of possibilities, this last factor provides a wider range of options. In order to restrict them main destinations have been classified into 3 categories: bodies *with atmosphere,* as Mars, bodies *without atmosphere* as Moon and bodies *with little gravity,* as an asteroid. The reason to execute this classification is that mentioned parameters are the main drivers to design the entry, descent and landing phase.

Once parameters to define each scenario have been presented, they have been combined offering 12 different scenarios as
Table 1 shows, where rows illustrate different configurations of scenarios combining number of microrovers and mission proposal and columns show destination of scenarios.

Option A corresponds with single rover as dedicated mission, B with multiple rovers as dedicated mission, C with single rover as piggyback mission and finally D with multiple rovers as piggyback mission.

Table 1 has been elaborated in order to know which of these combinations is the most important to develop. In order to value each possibility, it has been taken into account scientific and engineering criteria. The valuation has been rated in a set of qualitative values following the ascending scale of low, medium, high and very high interest.

Table 1: Scenarios

Scenario	Mars	Moon	Asteroid
Option A	Low	Low	Medium
Option B	Very high	High	High
Option C	Low	Low	Medium
Option D	Medium	Medium/low	Medium

Table 1 shows that single scenarios (options A and C) are not very interesting due to redundancy issues; it is preferable to have more than just one microrover to assure the completion of the mission even if there is a failure in one of them. Piggyback concept (options C and D) using some microrovers has been classed as medium interest. The main interest of this category is to bring microrovers as helpers of the main payload, for example to explore the landscape around the lander before the main payload is deployed.
To avoid the jeopardy of having just a microrover as it has been commented before, it has been thought to equip the mission with a pair of microrovers because adding more than a couple of them does not show any improvement. In this concept, microrovers are included in the lander but just as auxiliary payload. This is the

main reason to not consider these models as the aim of this paper.

Therefore, multiple and dedicated (option B) is the most interesting mission concept of the options that have been considered. Among the different destinations, the one that is the most interesting in science terms is Mars because although it is our neighbour planet, there is not a big knowledge about it; in fact, there are lots of myths around the red planet due to this lack of information. Thus, it is interesting to travel there in order to answer all questions that people and scientists have these days. This decision is supported by the two main Space Agencies: ESA and NASA. They are using their funding for researching in Martian missions. Their most challenging project is to send manned mission to the neighbour planet as Mars roadmap of these agencies show. [2]
With the purpose of doing it safely, to guarantee survival into Martian conditions, it is necessary to perform lots of research before the milestone of manned mission will be achieved.
As a conclusion of scenarios analysis, this paper is focused in a multiple and dedicated mission to Mars.

4. DESIGN CASE - MARS

This section explains main parameters of the mission corresponding to the chosen scenario.

4.1. Mission timeline

An interplanetary mission of this type is made up of 4 phases. Launch is the initial phase and it lasts from the beginning, when engines are turned on, until initial transfer orbit is reached. Then transfer phase occurs, which corresponds to travel through deep space, following a heliocentric trajectory from Earth to reach the sphere of influence of target body, in this case Mars. Once the mission reaches target body's atmosphere, entry descent and landing (EDL) phase starts. It is the segment where mission entries into the atmosphere, descents through it and finally lands on surface. And finally, surface phase is carried out after landing. This is the phase that provides scientific data, so it is the phase that gives significance to whole mission.
Although this mission has 4 phases this study just includes EDL and surface phases, which are focused on the delivery as the title of this paper states and because they are the starting point to study the whole mission.

4.2. Mission Composition

This mission is composed by different elements.
Microrovers refer to mission payload which is the responsible for the science experiments. The chosen microrover to be carried in this mission is the Nanokhod developed by v&HS.
Lander supports payload activities because it is not completely autonomous.
Rover System includes payload and lander.
Delivery Module is the system that provides deceleration in EDL phase.
Mission Composite is the part of the mission which entries to Mars atmosphere. Therefore it includes Rover System and Delivery Module.
Fig 1clarifies these concepts.

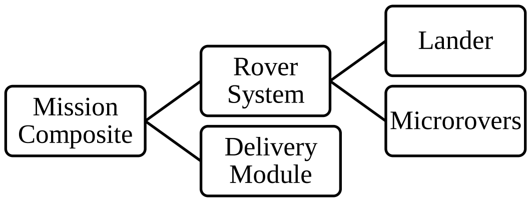

Fig 1: Mission elements

5. REQUIREMENTS COLLATION

Requirements are the formal language of the aerospace industry. They are a statement or a characteristic of something that mission needs and are classified into Top level requirements (TLR), Performance requirement (PR) and Functional requirement (FR) to indicate the importance level of each one. They are also divided into main elements of the mission in order to show which component the requirement is referring to.

This project performed a top-level requirements collation exercise, without exploring subsystem requirements in detail. The requirements document produced was then used to perform the preliminary design. They are grouped into major system elements as Mission Composite Requirements and Rover System Requirements.

6. SYSTEM BUDGETS

This section contains main subsystem budgets of lander and delivery module.

6.1. Rover System subsystems

Spacecraft lander is a protective shell that houses the rover and protects it before deployment and after gives them the required support to perform the mission such as power and communication.

Payload

As it has been previously introduced, payload of this mission is Nanokhod rover from vH&S. This mission will carry 4 Nanokhod; two of them are equipped with

a camera and an APXS instrument and the other two contains a camera and a MIMOS instrument. This distribution has been done considering redundancy issues.
Dimensions of each rover are 240x165x65mm and their mass is around 2300g each.
The most attractive characteristic of Nanokhod is its exceptionally high payload mass/total mass ratio around 0.5.
Nanokhod is a rugged, simple, yet reliable and effective rover, to carry instrument in the immediate surroundings of a lander. In order to maximize locomotion efficiently, the Nanokhod carries only what is strictly needed for moving and deploying instruments. No batteries or other power supply are on the rover, but it is provided with power and data exchange through a tether connecting it to the lander.

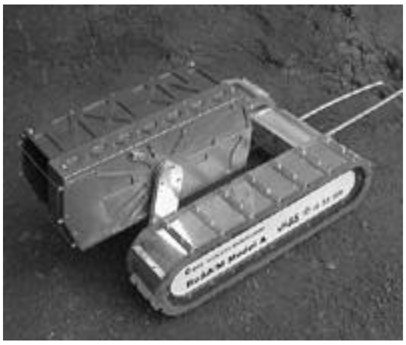

Fig 2: Nanokhod

Power

Sizing power subsystem involves dimensioning solar arrays and batteries to provide enough power to guarantee operation of payload mission, thermal safety conditions and communications.

Due to the limited size of microrovers power to allow their operation has to be provided through tethers. Thus, it is important to know activities that consume power like operating camera, APXS and MIMOS (the three scientific instruments that Nanokhod carries), controlling these operations, transmitting data from rover to lander and moving in Martian surface.

Elaborating a schedule of these activities and taking into account the amount of power that each one needs [3] it is possible to conclude that 160Wh are needed all day long in order to guarantee microrover operation. The schedule has been done considering that system needs maximum power constantly which is an overestimate but it is useful for a preliminary budget.

In order to maintain the lander inside a temperature interval to guarantee not only its operation but also its survival 5W of power is needed.

Collecting data is important but in order to be useful it should be transmitted to Earth and the latter action needs 10 W.
Note that power requirements for thermal and communication are obtained after sizing those systems. Whereas sizing power and thermal subsystems is an integrated process, power subsystem needs as an input thermal required power and thermal subsystem inputs are surface of solar arrays which are output of power subsystem sizing, communications and power subsystems are not iterative, power required by communication subsystem is just an output from communication study and an input of power sizing**.**

With the purpose of providing the required power lander includes solar arrays that will provide power during sunlight and batteries that will be charged during sunlight and will provide power during eclipse. Therefore, sunlight and eclipse duration should be known to perform the study; they have been obtained after simulating a one-year scenario with STK supposing that the chosen landing site is Amazonis Planitia (24.8º latitude and 196º longitude) due to its scientific and technical benefits. Result of this simulation is that 53.7% of a Martian day is sunlight and 46.3% of a sol receives no light.
It is important to notice that different activities are carried out in day and night; while during sunlight power is needed to guarantee payload activity and communication with Earth, in night time power is only needed for heaters and communications; microrovers don't operate during night.
Taking all these facts into consideration it is possible to say that solar array of 2.54m^2 with mass 9.55 kg and 4 lithium polymer batteries of 2.58 kg whose characteristics are obtained from [5] and take up 1.55 dm^3 are needed.
Notice in Fig 3 that solar arrays are folded before reaching Martian surface to avoid undesirable vibrations during all the previous phases and then they are deployed in order to receive sunlight as Fig 4 shows.

Thermal

It is needed to study thermal subsystem in order to guarantee the proper operation of the whole lander since every component works properly within an interval of temperature.
Taking into consideration solar panels, batteries, microrovers and communication components it is possible to conclude that non-operation range is from 263 to 298K and the operation range stands between 273 and 293K being the batteries the most restrictive component. These values have been extracted from [6] and from [3] the ones related with microrovers.

Thermal study is carried out with two different situations: hot case which occurs during sunlight and cold case which takes place during night. Solar, planet, albedo, convection, radiated and generated heat fluxes have been considered in hot case and it is found that lander reaches 288.6K which is a temperature within the limits. So, no external sources of heating or cooling are needed in this situation.

Notice that no solar flux is reaching the surface during night; hence just planet, convection, radiated and generated heat fluxes are considered in cold case. 176.5K is the equilibrium temperature in this case and it is completely out of limits. This means that a heater is needed in order to increase equilibrium temperature to at least the minimum operative temperature for critical components (batteries, electronics).

In order to solve this problem it has been thought to put all the lander into the minimum operative temperature, but it entailed high power which can be translated in high mass of batteries, so this option was ruled out. So the proper solution is that just the components whose lowest operative temperature is higher than cold equilibrium temperature would be heated. These components are batteries, electronic components and elements of communication subsystem, so they would be included in a warm box that maintains its temperature thanks to a heater. Due to it is only needed power to heat these components, the obtained power is lower than in the first proposed solution. Finally, it is obtained that 5W are needed to heat this warm box. It is important to remark that the lowest operative temperature of microrovers is also lower than the cold equilibrium temperature but, in order to save power, it has been considered that microrovers just work during sunlight and rest during night. So, non-operative temperatures of microrovers should be taken into account during night and it is higher than the cold equilibrium temperature, so there is no need to heat them.

Communications

Telecommunication is one of the most important functions of entry probes because it transmits to Earth all the science and engineering data that are the main goal of the mission. It is meaningless to send a mission to perform science research and to not receive its results.

Communication subsystem study includes data link budget and a coverage analysis.
From the schedule performed in power study it is possible to find the amount of data that is going to be generated, and therefore sent, daily and corresponds to around 2Mbytes.

Studying the link budget in X-band, with a frequency of 8GHz, and transmitter power of 10W it is possible to obtain a data rate of 2100bps which means that it needs a little more than 2 hours to send daily generated data. Thanks to this study it has also been possible to size the antenna; it will have a diameter of 0.5m.
Needed values for this calculation have been obtained from [3] and [7].

In order to check that this result is reasonable a coverage analysis is needed. The scenario with the lander located in Amazonis Planitia and ground station is chosen to be in Villafranca (40.45º latitude and -3.95º longitude) has been run through a year in STK and it has been obtained that mean access duration is more than 4 hours. However no daily access can be assured with this configuration, so it presents a problem to communication link because the assumption of transmit data daily is not possible. There are 3 main options to solve this problem: store data in Rover System when no access is possible, use two Earth facilities separated enough in longitude to guarantee a continuous access from Rover System or use an orbiter relay which means that Rover System transmits generated data to a satellite orbiting around Mars and then, this satellite sends this data to Earth facility.

All of these options have been simulated and after considering advantages and disadvantages or each option, the conclusion is that the best solution is to work with 2 Earth facilities, the second one is located in Perth whose longitude is -120º, to assure a daily communication from Rover System to Earth. Its main disadvantage is to get an extra facility, but it is cheaper than sending an orbiter.

Mass budget and distribution

Up to now, main lander systems have been described and roughly sized so the next step is to distribute them in order to have a physical view of the lander.
Most of the components are attached to the platform whose shape consists in a square that corners have been cut forming an irregular octagon composed by four big sides and four small sides. Solar arrays are attached to the big ones and the small ones contain ramps to allow microrovers descent to planetary surface, thus they have to be sized taking into account that they must be wide enough to allow microrover motion. Sizes of this platform are 1x1m where sides destined to attach solar arrays measure 700mm and as a result ramps wide is 212mm and 585mm long. All of these structures, platform and ramps, are made of aluminium 7075, commonly used in aeronautical industry.

The sides of the platform contain hinges to allow the deployment of ramps and solar arrays. Moreover it should be activated by a power source such as batteries contained in warm electronic box.
Once that main subsystems and platform have been sized it is possible to show a sketch of Rover System in both configurations: folded in Fig 3 and deployed in Fig 4 where blue elements are solar arrays, ramps are transparent white, warm electronic box is represented in gold, antenna is white and it is located just on top of warm electronic box and microrovers are represented as small boxes in aluminium colour.

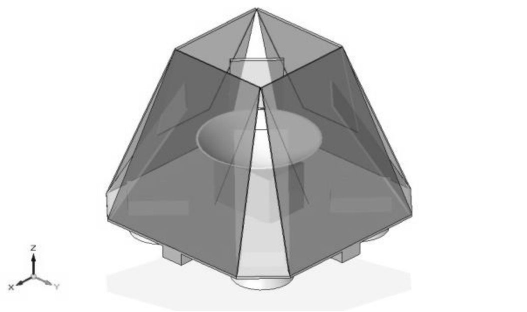

Fig 3: Rover System in folded configuration

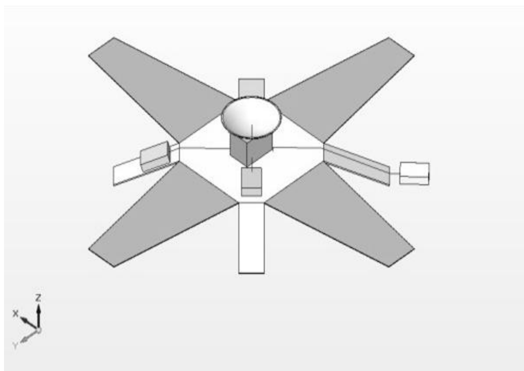

Fig 4: Rover System in deployed configuration

After setting all components it is possible to present mass budget of Rover System as Table 2 shows.

Table 2: Rover System mass budget

Subsystem	Mass [kg]
Payload (4 microrovers)	9.1
Power	12.2
Solar panels	9.5
Batteries	2.7
Thermal	2.5
Communications	7
Antenna	5
PC	2
Structure	57
Platform	25.8
Reinforcement	17.6
Ramps	13.6
Total	87.8

Low mass is a design driver, so it has been tried to select low mass components. However, to be conservative and cover all uncertainties a security factor of 30% is applied to total mass, resulting in a surface landed total mass of 114kg. This is technically well within the performance envelope for conventional aeroshell and parachute descent and landing strategies for Mars. [8] and [10]

6.2. Delivery Module subsystems

Delivery Module provides deceleration from entering into Mars sphere of influence up to it reaches the surface. In order to get this deceleration, aerobreaking is the chosen method for entry, a combination of parachute and thrusters will be used for descent phase and finally, it will land softly in Mars surface thanks to a landing gear.

This phase is one of the most risky parts of the mission, thus it is common to use methods that have been already tested in real scenario and no innovative methods are often implemented in EDL phase of a planetary mission.

Entry

The most iconic image of entry into a planetary atmosphere is a capsule being roasted in a fireball streaking across the sky. So as to protect Rover System of being burnt, it is housed in an entry capsule which offers thermal and structural protection. Thus, peak deceleration and peak heating are two needed parameters to size entry capsule.

Following method explained in [8], it is possible to obtain that peak deceleration is 94.6 $m/_{s^2}$ and it occurs at 44.08 km of altitude when the craft is travelling at 3.3 $km/_{s}$. Design parameters such as entry capsule surface and Mission Composite mass should have been included in the calculation procedure in order to obtain peak deceleration values; hence all EDL phase design is an iterative process. After reaching reasonable values for all parameters, most of them have been compared with already existing missions, it has been concluded that entry capsule surface is 3.8 m^2 which it corresponds to a radius of 2.3m and entry mass is 149.5kg.

Peak heating has been obtained as 20.58 $W/_{cm^2}$ and it happens at 55.3km of altitude when it is travelling at 4.65 $km/_{s}$. These values have also been checked with real Mars missions and notice that peak heating occurs before peak deceleration as theory indicates.
In order to survive to this peak heating, a thermal protection system (TPS) is required whose material has

been chosen to be SLA-561V, Super Light weight Ablator, as [8] and [10] indicate. Studying heat shield mass vs. total mass of already existing mission it has been concluded that 11.4 kg of TPS are needed.
Finally, entry capsule configuration is shown in Fig 5 where A corresponds to approximately height of lander in folded configuration which is around 0.66 m and B corresponds to the diameter of surface which is 2.3m. Total height of the capsule is 1.1m which leads to diameter/height ratio of 0.5m.
It should be reminded that these dimensions are restricted by launcher; Delta II is one of the most used launcher for Martian missions and it allows a diameter of 2.65m. Therefore, this mission capsule fits properly in this launcher.
The shape corresponds to a 70º sphere-cone which is blunt in order to withstand supersonic conditions of flight

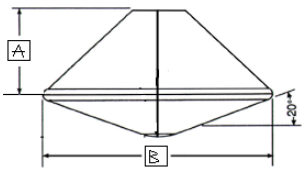

Fig 5: Entry capsule

Descent

Mission Composite is decelerated thanks to parachute and engines in descent phase, which starts when parachute is mortar-deployed; after that, heat shield is jettisoned and legs are deployed. The next step is to separate lander form parachute; backshell and parachute are also jettisoned. Then it is time to start the powered descent until few meters above planet surface where engines are shut down.

The first parameter to be fixed is Mach number where parachute is deployed. Taking values of already existing missions, parachute deployment Mach has been set around 1.9, thus it must carry a supersonic parachute.

Velocity profile of the mission is needed in order to check if the altitude where parachute is deployed is enough to provide the required deceleration before reaching the surface. Before obtaining velocity profile it is needed to have a density profile, so a study of it has been carried out considering some theoretical models and in-situ measured data provided by the MGS Radio Service Team of Stanford University. [9]

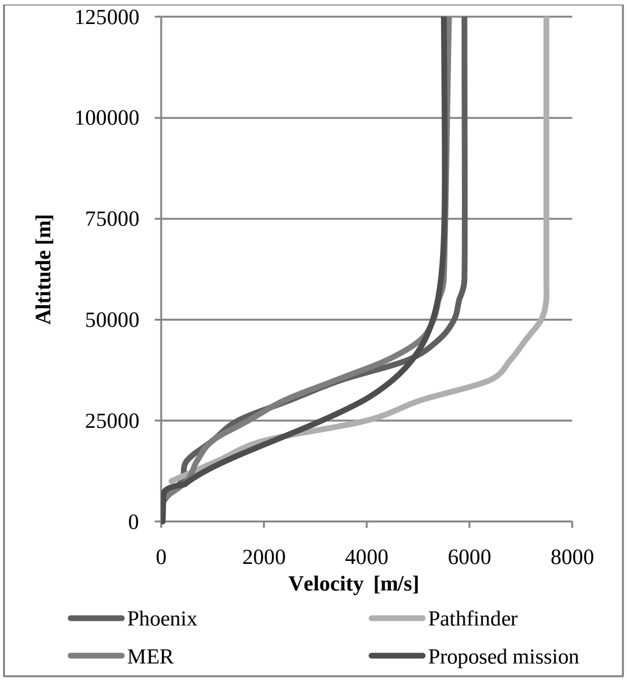

Fig 6: Velocity profiles of EDL phase

Notice the effect of parachute deployment in Fig 6 around 10000km of altitude where the curve becomes flat. Fig 7 compares velocity profile with and without the effect of parachute where decelerator effect of the parachute can be seen in the red line. It can be concluded that mission will carry a disk gap band parachute whose diameter is 11m deployed at 9100km above MOLA (Mars Orbiter Laser Altimeter). This kind of parachutes is advisable for March numbers up to 2 and the diameter has been obtained after the iteration process.

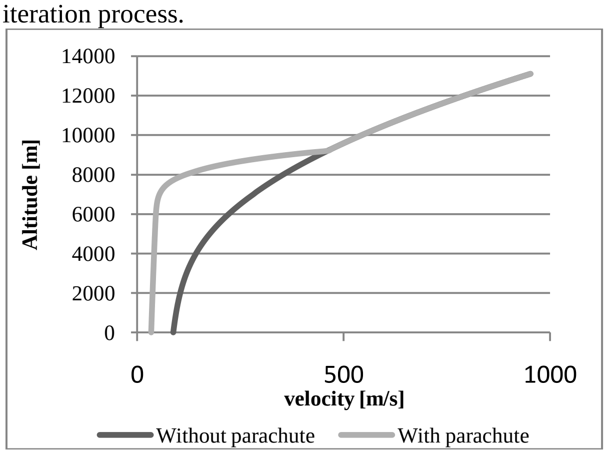

Fig 7: Velocity profile with and without parachute effect

Already existing Martian missions have parachutes whose diameters vary from 10 to 16.2m; hence the obtained value is reasonable because stands within the limits.
Rating parachute diameter with parachute mass of three previous Mars missions it is obtained that

parachute mass is 17.88kg. An important parameter of a parachute is its drag coefficient; it has been obtained from [11] and it is 0.55.
Heat shield separation takes places nearly 1 km after than parachute deployment, precisely at 8km above MOLA. It offers a mass reduction to the whole of 11.4kg.

Lander separation from parachute occurs at 4.2km where it is descending at 40 $m/_s$. After that, Delivery Module is almost completely deployed, only rests fuel, and a throttled descent starts. Hydrazine is the chosen fuel which specific impulse is 240s and 6.25kg are needed in order to perform a reduction of velocity (ΔV) of 40 $m/_s$. Engine is shut down few meters before arriving to surface in order to do not alter Martian surface.

Landing

After every device of EDL has worked properly, Rover System reaches Martian surface at nearly 0 vertical velocity; thus landing gear which is composed by 4 legs, just have to be able to cope with this residual vertical velocity that can be caused to free-fall from the height at which thrusters are shut down.

Legs length is 30cm and its cross section is an aluminium tube whose external diameter is 5cm and the internal is 4cm. Moreover these legs should incorporate a mechanism in the end that touches surface to precisely provide a surface of contact with the terrain and some method to avoid that legs fold or deploy.

An important aspect to assure a safe landing and avoid hazards is to provide EDL phase with active guidance, navigation and control instruments. Nevertheless it is out the scope of this paper, it has been mentioned just to be considered in future studies or improvements.

Finally, it should be added that total mass of Rover System is 35.5kg, without taking into consideration landing gear mass because it is not significant in comparison to the others. Hence it leads to a Mission Composite of 149.5kg.

7. CONCLUSIONS

This paper presents a brief summary of the thesis project of the author, conducted at the School of Industrial and Aeronautic Engineering in the Technical University of Catalonia during 2009 under the supervision of Professor Ed Chester.
The principal objectives were met, by analysing the delivery and mission support requirements for multiple microrovers. The mass and power budgets produced are suitable for a small, low-cost mission implementation, but no cost estimates have been performed at the time. The Nanokhod provides an excellent reference model to design mission concepts around, and the recommended next steps are as follows:

1. Conduct a design iteration adding a subsystem level of detail to each major block, leading to a refinement in all system level budgets.
2. Perform a cost estimation
3. Asses cruise stage and launch alternatives to complete the mission scenario. This would partly be driven by landing site election, which out of scope thus far. Ongoing MER and upcoming MSL mission will provide valuable inputs to a site selection process for microrover exploration.

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