EXTREMELY LOW MASS SPHERICAL ROVERS FOR EXTREME ENVIRONMENTS AND PLANETARY EXPLORATION ENABLED WITH MEMS

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ABSTRACT

The Spherical Mobile Investigator for Planetary Surfaces (SMIPS) concept is aiming to create a low mass and highly flexible long range robot explorer for extreme environments such as planetary surfaces. A major driver of the concept is to be a complement to existing large wheel based robots with limited action ranges.

The SMIPS introduces network based sensor systems with action radii of up to 100 km while weighing about 3.25 kg per robot. The robot diameter is 0.44 m. Several instruments can be carried by the robot. Microelectromechanical (MEMS) technologies are used to reduce the system weight and increase the system performance, especially regarding to instrumentation and power generation.

This paper discusses the spherical robot concept in general and how it can be applied to multipoint sample return or other missions to Mars where the mission is enabled with direct entry of each miniaturized spherical robot. The robot system designed for entry from low Mars orbit weighs 5.5 kg including the heat shield and parachute. The impact during landing is estimated to 75-100 g.

Nomenclature

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<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>σ</td>
<td>Stefan Boltzmann’s constant</td>
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Subscripts:

- o: Mars surface
- 1, ∞: prior to shock front
- 2: behind the shock front
- avg.: average
- CF: continuum flow
- FMF: free molecular flow
- HS: heat shield
- ref: reference
- s.p.: stagnation point

1. INTRODUCTION

This paper will explore the possibility to use a spherical robot utilizing Multifunctional Micro Systems (MMS) for planetary exploration. In addition, the scope of the paper will be to present a robotic design concept using the mentioned technologies that can survive re-entry on Mars without a dedicated lander.

The term Microelectromechanical Systems (MEMS) is used in this paper, although while MEMS is commonly referred to as Micro Systems Technology (MST) in Europe they are manifestations of the same. In addition, Multifunctional Micro Systems (MMS) are used for larger and more complex MEMS systems. The MMS concept has been derived by the Ångström Space Technology Centre for extreme miniaturization of nanosatellites [1, 2].

2. ROVER DESIGN

The single most important issues are mechanical reliability and secondly power generation for long range and time operation. It is important in this case with a spherical robot to maximize the use of the shell since it is the interface to the body of interests. Therefore the shell should be multifunctional in the sense that it can be used for more than just locomotion.
The spherical shape of the robot is good for power generation since it will have a constant area facing the sun, unless being shadowed. Using a layered shell, where the outer layer is manufactured transparent and by mounting small modules of thin-film solar cells on the inside of the transparent layer a good power generation can be assured.

Fig. 1 illustrates the basic concept of the SMIPS robot.

![Fig. 1. Basic illustration of the SMIPS robot with extendable endcaps with antennas, open for cameras and scientific equipment.](image1)

Fig. 2a and 2b illustrates the locomotion mechanism of the robot. A pendulum is connected to a main axle that runs through the whole sphere. One motor raises the pendulum which moves the centre of mass

![Fig. 2. SMIPS locomotion model and possible movement description. Fig. 2-a illustrates the basic locomotion principle using a main axis and a pendulum. Fig. 2-b illustrates the driving locomotion movements, e.g., raising the pendulum perpendicular to the main axis and tilting the pendulum along the main axis.](image2)

The robot shell needs to be designed to incorporate solar cells, instrumentation, and thermal management. This is done with an 11-layered shell structure. This is illustrated in figure 3 together with the interconnection from the shell to the main axis using a flexible cable. The flexible cable connecting the shell with the main axis can be wide and support many signals, although, there are a limited number of signals that can be linked to the moving pendulum and there should as many signals as possible be serial in nature.

The layers are not drawn in scale and the thickest layer is support layer with a few millimeters using PBO or Spectre. The surface layer and the instrument layer are both transparent and are deposited on the protective layer 9. The instrument layer will hold thin-film instrumentation that will cover very small portions of the solar cells underneath.

The CIGS thin-film solar cell layer is typically 2 micro meter in thickness. The vias feeding the instrument layer and collecting the power from the solar cells can be machined with classical tools, while MEMS vias are used in the transparent coatings (layers 6 and 8).

Thermal management in the shell is implemented as a thin-film light modulation layer. This layer can change transparency properties and thus act as a thermal control system. The modulation layer is similar in technology as Variable Emittance Panels developed for nanosatellites. The inner protective layer 1 is preferable also spray coated over the conductors in the shell and the simple electronics to collect the power from the solar cells. This layer is mainly implemented to increase handling tolerances and can be seen as the protective coating on a traditional PCB.

![Fig. 3. Illustration of a 11-layered MEMS enabled multifunctional shell that include power generation and scientific instrumentation.](image3)

Miniaturization of electronics using Multi-chip-module techniques.

The first real field tests of the SMIPS concept has been made in Uppsala with a commercial robot from Rotundus AB. This robot uses a PC104 board for the on-board electronics. The size of a PC104 board is about 10 x 10 cm and 2-5 cm in height.

The size of a PC104 can be reduced in volume a factor of 25 times using Multi-chip-module (MCM) technology, where all parts on the PC104 is replaced with their respective naked die and put inside a silicon package. This will allow the SMIPS to carry a 500 MHz to 1 GHz processor, 512 MB of RAM, a 10 GBit solid state mass memory, UHF and s-band communication.

The on-board electronics module is located between the batteries which provides roughly 5-7 cm of radiation shielding from all sides.

Related work

The locomotion principle of the SMIPS is derived from a Swedish patent held by Per Samuelsson from 1992 [3]. Michaud and Caron have developed a spherical robot “Roball” which is very similar to the SMIPS concept with the largest difference in the location of the DC-motors [4]. Both concepts use a design where
motors are attached to the sphere for locomotion. Roball uses a plate design in the center which differs from the hollow main axis of SMIPS. Using a main axis it is possible to split the weight on the pendulum, thus allow for 90 degree tilting (the weights move past the main axis on each side). This design can let the robot to tilt and stand on one of the side endcaps and allowing for simple drilling using a stowed drilled inside the axis. This is however not pursued by the authors at this moment. JPL investigated a similar locomotion principle in 1997 [5, 6]. The JPL solution had a major difference in the motor position, where the main driving motor is placed at one of the ends of the main axis. Furthermore does the JPL rover have a much larger diameter in order to have the option to be wind driven. The rover described by Jones and Yavrouian at JPL is also very similar to the SMIPS. The main difference and improvements between SMIPS and the JPL robot is lower center of mass (C.M.) that originates from a motor locator on the pendulum instead than on the main axis. The JPL robot shares the ability to utilize stereo-vision by mounting cameras in the ends of the main axis. Halme et al. have constructed a spherical robot with a single wheel resting on the bottom of the spherical shell [7]. The control unit is located above the wheel and by using two motors it rotates the wheel to create the driving torque. By rotating the wheel around its vertical axis control of the heading of the robot is made possible. This design offers two inputs to control the motion. The system is nonholonomic and is described by non-linear equations. Bicchi et al. developed a robot consisting of a spherical shell with a small “car” resting on the bottom [8]. The car is kept at the bottom by its own weight. Bhattacharya and Agrawal presented a design based on three rotors, where two of them move together and can be considered as one rigid body [9]. One of the rotors is mounted on the vertical axis and the other two are mounted on the horizontal axis of the spherical robot. It is the angular velocities of these internal rotors turning on themselves that make the robot move. An approach based on the distributed masses inside the spherical shell was introduced by Mukherjee et al. [10] and implemented by Javadi and Mojabi [11]. There are a few additional commercial spherical robots presented by Michaud and Caron, but these systems also differ from the propulsion system of SMIPS [4]. The Center for Distributed Robotics (CDR) at University of Minnesota has developed a series of small robots comprising a tube shape and wheels in each end [12].

3. GUIDANCE AND LOCOMOTION

The robustness is one of the main features of the robot. The driving unit has no shock providing contact with the shell besides the contact with the diametric main axle via the transmission system. That makes the robot to an impact safe system. There are only two points where a direct impact could cause some damage. These are the attachment points of the main axle to the shell. The developed system solves this problem by offering a telescopic main axle with elastic joints, which make these points impact safe.

The basic principle of SMIPS locomotion is based on the disturbance of the system’s equilibrium by moving its centre of mass. The position of the centre of mass is controlled by an inside construction called Internal Driving Unit (IDU). IDU can be approximated to a spited pendulum. The pendulum can rotate around the main axle in plane perpendicular to the main axle and in the plane created by the pendulum and the main axle. Rotation of the pendulum is controlled by two independent motors mounted inside on the IDU and creating the possibility to place the centre of mass at any angle around the vertical line passing through the centre of SMIPS and the point of contact with the ground. According to the above, SMIPS have the capability to move in any direction from rest by moving its centre of mass in that particular direction.

A spherical robot represents a challenging control problem with multidimensional and nonlinear dynamics. There have been presented a number of solutions to control a spherical robot, e.g. [14, 15, 16], most of these have used an analytical approach for solving the control problem. This approach has often resulted in heavy computational problems. In this paper we describe an alternative approach using reinforcement learning to design a controller for a spherical robot. The robot carries an Inertial Navigation System (INS) consisting of 3 accelerometers and 3 rate gyroscopes installed in exactly orthogonal x, y, z directions. The state of the robot can be represented by the vector,

\[ s = [x, y, z, \phi, \theta, \omega, \alpha, \beta, \dot{x}, \dot{y}, \dot{z}, \dot{\phi}, \dot{\theta}, \dot{\omega}, \dot{\alpha}, \dot{\beta}] \]

where \((x, y, z)\) and \((\dot{x}, \dot{y}, \dot{z})\) describe robots position and velocity, while \((\phi, \theta, \omega)\) and \((\dot{\phi}, \dot{\theta}, \dot{\omega})\) describe orientation and angular velocity of the pendulum inside the robot. Values of \((\alpha, \beta)\) and \((\dot{\alpha}, \dot{\beta})\) describes orientation and angular velocity of the robot shell. The robot is controlled via a 2-dimensional action space \(a_1\) - the main driving motor for the forward/backward control and \(a_2\) - the steering motor for the left/right control. It has been shown [13] that using the PEGASUS reinforcement learning algorithm one can stabilize and successfully control a flying helicopter. An approach similar to the one described in [13] is used to control SMIPS.

4. ENABLED MISSION SCENARIOS

The Mars entry analysis detailed under section 5 shows that it is feasible to accomplish a safe landing of the robot without the need of a dedicated lander. The lander is replaced with a protective heat shield cover.
on each robot. However, in order to be mass efficient, the robot must be capable of handling an impact of 75-100g at touchdown on the Martian surface. This conclusion can be used to design quite novel mission profiles. One mission that could be enabled is a multi point sample return mission. Fig. 4 illustrates how a spacecraft enters low Mars Orbit and releases a number of SMIPS which enters and lands on Mars autonomously. These robots can be equipped with a small drill and take samples and drive back to a lander. It is risky to do this, because of cracks, valleys etc that may hinder the robot from driving back to the lander. However, this can likely be solved by careful planning of the landing sites.

![Mars Diagram](Image)

Fig. 4. Illustration of a multi entry mission profile using several SMIPS robots. One application could be a multipoint sample return.

A multi sample return mission using 8 SMIPS robots would weigh 44 kg excluding the mass on the transport vehicle. These 8 robots can be deployed over an area of 100 square km. The lander that will pick up the samples and bring them back to Earth will reduce its landed mass by 44 kg.

One SMIPS robot is expected to be able to carry 500 grams of samples using a drill system located in the main axle. The limited weight of the robot and the severe mass restriction limits the drilling dept. The authors expect a drilling depth of about 20 cm. A total of 8 SMIPS robots could collect a total of about 4 kg samples.

The SMIPS flight hardware costs is in the order of $5M for two robots which brings the total mission cost (excluding operation) for 8 robots to about $20M.

The SMIPS can be used for many other purposes. If launched together with a larger wheel based rover it can act as a fast robot doing preliminary analysis of interesting areas and give the science principal investigators information on how to optimize the science value.

For human missions the SMIPS can be used as a tele-operated camera or miniaturized base inspector. The robots can carry visual cameras; IR cameras etc. and detect changes on structures on the surface (in case the base is below the surface). A number of SMIPS robots can easily be carried by an astronaut due to their low weight. The SMIPS can be equipped with miniaturized dosimeters and Geiger-Muller detectors to analyze the status of Lunar or Mars based nuclear generators which may be hazardous to humans.

5. MARS ENTRY ANALYSIS

Modelling the Entry, Descent, and Landing of the SMIPS on Mars

The ballistic coefficient B is defined as

\[ B = \frac{m}{c_d \cdot A_{ef}} \] (1)

This results in a ballistic coefficient of some 25kg/m² for SMIPS, which is very low compared to that of other spacecrafts\(^1\). The impact of this low value as well as scale effects onto the overall mission will now be discussed\(^2\). First, one can derive the drag resistance during atmospheric entry as:

\[ F_D = \frac{\rho}{2} v^2 \cdot c_D \cdot A \] (2)

The atmospheric density is a function of altitude and can be approximated through an exponential function (\(\rho_o=0.02\text{kg/m}^3, H=11.1\text{km}\)); however, in the numerical analysis outlined below, tabulated values based on the results of US-American Mars probes [22] were used for altitudes in excess of 30km (see Fig. 5).

![Mars Model Atmosphere](Image)

Fig. 5. Mars Model Atmosphere

Heat transfer to the SMIPS during Atmospheric Entry

The process of descending down to the surface of Mars starts with the hypersonic entry into the atmosphere. The atmospheric entry of spacecrafts has been subject of investigations already since the early days of spaceflight [18, 19]. The approach chosen here is based on the energy/momentum equilibrium and utilises the Stanton number. During re-entry, the momentum of the

\(^1\) Typically, values range from 250 (for capsules) to 2000kg/m³ (for winged crafts).

\(^2\) For further analysis of the impact of low ballistic coefficients on atmospheric entry see [17].
descending spacecraft transfers to the surrounding atmosphere. This is governed by the momentum equilibrium

\[ m \cdot \dot{v} = -\frac{\rho}{2} v^2 \cdot c_D \cdot A_{ref} \]  

(3)

The heat transferred to the descending SMIPS can be calculated using the Stanton number St:

\[ \dot{Q} = \frac{\rho}{2} v^3 \cdot St \cdot A_{ref} \]

(4)

Combining equations 3 and 4, one obtains

\[ \dot{Q} = -\frac{m \cdot v \cdot \dot{v}}{c_D} \cdot St \]

(5)

Since

\[ E_{kin} = \frac{1}{2} m v^2 \Rightarrow \dot{E}_{kin} = m \cdot v \cdot \dot{v} \]  

(6)

one can simplify formula for \( \dot{Q} \) further to

\[ \dot{Q} = -\frac{St}{c_D} \cdot \dot{E}_{kin} \]

(7)

According to [18] and supported by experimental data of [20], the Stanton number of a sphere can be approximated with

\[ St = \left( \frac{Re_2}{2.1^2} + 1 \right)^{-\frac{1}{2}} \]

(8)

wherein \( Re_2 \) is the Reynolds number behind the shock front. For low Reynolds numbers (high Knudsen numbers), the above formula approaches

\[ St_{CF} \approx 1 \]

which describes continuum flow conditions, whereas for high Reynolds numbers (low Knudsen numbers) the formula approaches

\[ St_{FMF} = \frac{2.1}{\sqrt{Re_2}} \]

(9)

which describes free molecular flow. The Reynolds number of a sphere is defined as

\[ Re = \frac{\rho v d}{\eta} \]

(10)

wherein \( \eta \) is the dynamic viscosity, which is approximated by the (temperature-dependent) viscosity of carbon dioxide.

Fig. 6. Stanton over Reynolds Number

The relation between the Knudsen number

\[ Kn = \frac{\lambda}{d} = 1.26 \cdot \frac{Ma_{\infty}}{\sqrt{\kappa}} \]

(11)

and the Reynolds number after the shock front can be derived by simplifying the hard sphere gas viscosity law [20]:

\[ Re_2 = 3.33 \quad \frac{Kn}{Ma_{\infty}} = 2.64 \cdot \frac{Re_2}{Ma_{\infty} \cdot \sqrt{\kappa}} \]

(12)

The drag coefficient of a sphere at hypersonic velocities is given by

\[ c_{D,CF} = \frac{1}{2} \left( \kappa + 3 \right)^{-1.3} = 0.935 \]

(13)

in continuum flow and

\[ c_{D,FMF} = 2 \]

in free molecular flow

Convective and Radiative Heat Exchange

Not all the heat flux that is transferred to the SMIPS is actually penetrating the heat shield. Some is also radiated to the outside. Assuming that the thermal energy is first absorbed only by the heat shield, and not (yet) by the rest of the SMIPS, the following equation describes these phenomena:

\[ \dot{Q} = m_{HS} \cdot c_{p,HS} \cdot \frac{dT_{HS}}{dt} + \varepsilon \sigma A_{HS} T_{HS}^4 \]

(14)
Knowing \( \dot{Q} \) already thanks to the deliberations above, one can know solve for the temperature change of the heat shield (either analytical or numerical):

\[
\frac{dT_{\text{HS}}}{dt} = \frac{1}{m_{\text{HS}} \cdot c_{\rho,\text{HS}}} \left( \dot{Q} - \varepsilon \sigma A_{\text{HS}} \cdot T_{\text{HS}}^4 \right) \quad (15)
\]

This formula neglects temperature differences in the heat shield over the surface of the sphere. In reality, this case is reached if the sphere is spinning during re-entry. More detailed analysis has to show whether such a spinning movement would be preferable with respect to the design compared to the selection of a fixed stagnation point (through the position of the centre of mass significantly away from the centre of the sphere).

In that case, the \([19]\) correlation based on Lees theorem and the special heat transfer coefficient \( K \) delivers a stagnation point heat flux of

\[
\dot{q}_{s,p} = K \cdot \left( \frac{P_{\text{w}}}{r_{\text{pose}}} \right)^{0.5} \cdot v_n^3 \quad (16)
\]

om there, also using the work of \([18]\), the heat transfer distribution over the entire heat shield surface normalised with the stagnation point heat transfer rate can be derived. For an overview over various approaches for solving the heat transfer problems analytically, see \([21]\).

### The Heat Shield

Since with a diameter of the protective sphere around the SMIPS will be close to 0.5m, the thermal protection layer with a thickness in order of approximately 1cm can be in a first analysis be treated using the simpler formula for the planar case:

\[
\frac{\partial T}{\partial t} = \frac{\lambda}{\rho \cdot c_p} \frac{\partial^2 T}{\partial y^2} \quad (17)
\]

With the solution for the partial differential equation with a Neumann boundary condition, the temperature change at the inside of the heat shield can be approximated with the formula

\[
\Delta T = \frac{\dot{q}_{s,p}}{\lambda} \left( \sqrt{\frac{4 \lambda \cdot t}{\rho \cdot c_p \cdot \pi}} \cdot e^{-\xi^2} - \delta \left[ 1 - \text{erf} (\xi) \right] \right) \quad (18)
\]

wherein \( \xi \) is a dimension free location/time coordinate and \( \text{erf}(x) \) is the error function:

\[
\xi = \frac{\delta}{2} \sqrt{\frac{\lambda \cdot t}{\rho \cdot c_p}} \quad \text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-z^2} dz \quad (19)
\]

Using a maximum allowable temperature increase of 100K on the inside and the material properties of a heat shield substance such as e.g. Norcoat Liège HPK-FIH\(^3\), a stagnation point shield thickness of only some 10mm is calculated. The exact shield thickness and temperature distribution during entry can only be achieved through more detailed numerical (CFD) simulations, since a Neumann boundary condition is only a rough approximation of the heat flux peak of a hypersonic entry.

### Descent and landing

The SMIPS will have a stationary free fall velocity below 150m/s. On Mars that relates to Mach numbers in the order of 0.55 to 0.65. These low values will probably already eliminate the need for a drogue chute and reeling (which would both increase complexity). Instead, an elastic band (shock cord) would take over the task of absorbing the opening forces of the parachute (the opening shock is 5 to 9g). In subsonic velocities, conical ribbon chutes usually have preferable drag coefficients. Other chute types to be considered are ringsail chutes (which all manned capsules of NASA used) and disk-gap-band chutes (as used by Mars probes such as e.g. Viking). Reaching a \( \text{c}_D > 0.55 \) should be easily achievable, with the potential to go up to 0.8 with the ringsail chute. With these values, and a maximum impact velocity constraint of the SMIPS of 25m/s that results in a minimum chute diameter of

\[
F_{\text{grav}} = F_{\text{drag}} \Rightarrow m \cdot g = \frac{D^2 \cdot \rho \cdot \pi}{8 \cdot v^2 \cdot \text{c}_D} \quad (20)
\]

\[
d_{\text{ref}} = \sqrt{\frac{8 \cdot m \cdot g}{\rho \cdot v^2 \cdot \text{c}_D \cdot \pi}} \approx 2.2m
\]

The exact diameter depends on the maximum terrain altitude that the SMIPS still has to be able to land at (the higher this altitude is, the larger the diameter will have to be, thus decreasing the payload capacity – here, a density value of 0.02kg/m² was assumed). According to design guidelines \([23]\), such a chute will weigh under 0.5kg; hence, for the total landing system mass (including container and deploy mechanism) in this context a value of 0.85kg has been chosen - over 20% of the system mass after separation from the heat shield, a higher / more conservative ratio than in other missions. The chute material would be kevlar, mylar, nylon or combinations of them. The chute container could be a frustum shape appendix to the sphere, which would force the sphere into a defined orientation

\(^3\) Norcoat Liège HPK-FIH was used e.g. on the Huygens probe. It properties (\( \lambda=0.08W/(mK) \), \( c_p=2.4kJ/(kgK) \), \( \rho=470kg/m^3 \)) are superior to those of the standard ablator SLA561V used on all NASA Mars probes.
during entry. The same fixture, that keeps the two hemispheres of the heat shield together, would also serve as chute ejector. Upon chute release signal, this rod/rope would be cut by a pyro actuator and the chute container would separate from the sphere thus serving as a drogue chute and deploying the main parachute. In the same moment, the frontal heat shield hemisphere would also fall off.

An alternative system based on a solid brake rocket motor was also investigated. Due to the more stringent requirements for initiation and the question of stabilisation, preference was however given to the chute system. The parachute ejection is much less stringent in terms of right timing; it can be initiated by either a pressure sensor, a ground sensing radar or by a clock. An open issue is the separation of parachute and rover from each other (shortly prior to touchdown or after?). A chute separation immediately after touchdown would avoid the need for an altitude measuring system (such as ground radar). Whether the SMIPS however runs the risk to get stuck under the parachute after touchdown only hardware tests can show.

Numerical Results

The simulation is based on the formulas and assumptions outlined above and starts at the same interface that also other direct entry missions (such as the Mars Exploration Rovers and the Mars Pathfinder Mission) take as the point of origin. That means typically a velocity of around 7.5km/s at an altitude of 125km with a descent angle close to 20°. As analytical approximation already predict, the maximum of atmospheric deceleration ($a_{\text{max}} < 21g$, at $t \approx 83s$) will occur after the (quite moderate) maximum of the specific stagnation point heat flux ($\dot{q}_{s.p.} = 100kJ/m^2$, at $t \approx 74s$).

The temperature of the heat shield will always be significantly less than 2000K throughout the entry, therefore there is no requirement for the development of new materials. However, it is too soon to exclude the potential occurrence of practical problems during the design and manufacturing of a heat shield with dimensions in this small order of magnitude.

6. CONCLUSIONS

The system and mission analysis of the Spherical Mobile Investigator of Planetary Surface (SMIPS) shows that it can be used for multi sample return
missions. It can further act as a micro base inspector for human Lunar and Mars bases where it can perform vital functions, such as being a manoeuvrable camera system or inspect the radiation level from nuclear power plants. Modern multi-chip-techniques (MCM) can reduce the electronics by 25 times in volume and thus allow the critical on-board electronics to be stored between the batteries boosting the radiation protection from simply the 2 mm shell to 5-7 cm from all sides. The results outlined above give a first indication that the design of a micro-rover system able to enter the Martian atmosphere and safely land on the surface faces no showstoppers as of yet. All stresses, accelerations, and temperatures are well within the mission envelopes of missions flown some 30 years ago. The point of origin corresponds to a direct entry mission; mission scenarios involving SMIPS departure from an orbiter (similar to Beagle II) would face much lower stresses during atmospheric entry, hence result in higher payload fractions.

Yet to be improved needs to be the variability of the adiabatic exponent $\kappa$ in the gas dynamics analysis. In later stages of the project, a thorough CFD and thermal analysis will become necessary. In particular the analysis of the phenomena within the bow shock and the heat shield will play a crucial part in this context.

References

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