Strategies to utilize advanced heat shield technology for high-payload mars atmospheric entry missions

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A R T I C L E   I N F O

Keywords:
Mars
EDL
Supersonic-Retropropulsion
Re-entry
Flexible Heat shields

A B S T R A C T

Present Entry, Descent and Landing (EDL) technology for interplanetary missions does not have the capabilities to meet the demanding requirements that come with future missions. A popular target for such missions is Mars and today efforts are made to send manned as well as sophisticated robotic probes to the Martian surface. Because present EDL technology has reached its limits, fundamentally new approaches are needed to significantly extend capabilities. Systematic evaluation of novel EDL technologies and optimization of EDL strategies are crucial needs for conceptual design. A computational framework will be presented tailored to enable systematic EDL analysis with special regards to novel EDL technology and event strategies. The benefits of flexible heat shield concepts that come with liberties in the choice of the ballistic coefficient will be shown in comparison with solid shield alternatives for payload classes of 2, 25 and 40 tonnes to show potential for manned and robotic missions. Furthermore, benefits of the new methodology for novel EDL event strategies are presented and discussed. The introduced methodology will help designers exploit new directions for conceptual design regarding EDL systems in terms of entry mass optimization and mission capabilities.

1. Introduction

Today Mars is a popular target for prospective planetary missions, robotic as well as human. Since the first lander tried to reach the Martian deserts in 1971 almost half of all landing missions to the red planet have failed, which highlights the challenging nature of this target. Faced with these appreciable challenges engineers and scientists focused significant effort and resources on development of sophisticated and reliable space vehicles for fulfilling many challenges of such missions. Nevertheless, even the most recent missions are based on technology developed during the Viking program in the 1960’s. Present Mars missions Entry, Descent and Landing (EDL) capabilities are reaching their limits [1] and for future extra-terrestrial exploration missions, it is essential that we overcome the limitations of today’s technology.

A particular problem facing Mars entry vehicles is the thin atmosphere and relatively high gravity, which restricts the maximum ballistic coefficient reachable for classic rigid blunt body heat shield designs [2]. The ballistic coefficient (BC) is a characteristic variable to describe atmospheric entry devices and is defined as follows:

\[ BC = \frac{m_0}{C_A A} \]  

(1)

Where \(m_0\) is the entry mass, \(A\) the surface area and \(C_A\) the average drag coefficient. For a classic blunt body design the key issue is that for a given maximum ballistic coefficient the capsule diameter increases proportional to \(\sqrt{m_0}\). A maximum BC for Mars entry capsules of 150 \(\text{m}^2/\text{kg}\) has often been quoted [1] and relies on a classic three event EDL maneuver using a supersonic parachute. The use of alternative final event technology is likely to allow higher BC, but a limit on BC remains for every rigid EDL design facing thin atmospheres. Note that although the drag coefficient influences the diameter in this calculation, it has been shown that the drag coefficient is largely insensitive to lift-to-drag ratio or heat shield shape changes and can be approximated as a constant in the range of \(1.4 < C_D < 1.6\) over a wide range of hypersonic Mach numbers [3]. Note that this assumption is only valid for blunt body capsule shapes. Fig. 1 shows the relation between heat shield diameter and mass for classic capsule technology with different BC. Also outlined is the zone reached by past Mars missions (green box) and the zone engineers have to reach to enable human Mars missions (blue box), based on recent studies [4]. One can see the significant gap between present capabilities and future demands. Also it becomes obvious that blunt body concepts for high payload atmospheric entry have to provide large frontal areas to meet given ballistic coefficient constraints.

To bridge this gap various alternative EDL designs have been proposed and examined [5]. One of the most promising options today is the class of extendable heat shields. Fig. 2 shows a deployable heat shield...
shield concept in its stowed and deployed configurations, alongside a photograph showing the layer structure of a flexible heat shield fabric. To comply with given maximum launcher fairing diameter limits these shields are made of a flexible material. Unfolded to full size in space they can reach the massive diameters needed for high payload EDL missions (see Fig. 1). Present launchers can accommodate capsule configurations, alongside a parachute and a retro-propulsion terminal descent event. All Mars missions to date have adopted this approach, with only minor changes in the final events choice [1,11]. As such engineers are less experienced when it comes to compiling and optimizing EDL sequences tailored to the demands of high payload missions. In order to capitalise on recent advances in technology, new methods are required to systematically compare given alternatives in a precise manner and identify optimal solutions.

To this end, a methodology to effectively compare different flexible heat shield technologies in combination with various EDL event sequences is presented in this paper. The primary aim is to relate a given payload mass directly to resulting entry masses, independently from details of the heat shield technology. Accordingly, low resulting entry masses correspond to high mass efficiencies of candidate designs. Furthermore the methodology can be used to find optimized configurations in event sequence composition and vehicle design.

This article proceeds with a short overview over the utilised modeling and computational methods, followed by a discussion on potential EDL technology and event design options. Afterwards the methodology to evaluate EDL technology will be presented. Applied to two candidate mission designs, the value of this approach will be shown. Finally the results will be discussed, concluded by recommendations for EDL architectures for future Mars missions.

2. Computational framework

A three degree of freedom model has been used to compute the trajectories for the following analysis. The code is written in C++ and uses the “odeint” library to solve ordinary differential equations (ode’s).

To compute the trajectory, equations for position and velocity vectors have to be solved. Time derivations of the position vector are defined as follows:

\[
\dot{\text{long}} = v \cos(\phi) \frac{\sin(\chi)}{r \cos(\text{lat})}
\]

\[
\dot{\text{lat}} = v \cos(\phi) \frac{\cos(\chi)}{r}
\]
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