(Preprint)

ENTRY, DESCENT AND LANDING SYSTEM FOR CUBESAT-SIZED DROP-OFF PAYLOADS

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CubeSats are emerging as low-cost platforms to perform space exploration. CubeSats are compelling because they can exploit unutilized mass and volume aboard a large interplanetary spacecraft that would otherwise be ballast. Current CubeSat designs envision flyby or orbiting spacecraft, however, rarely do they envision landers. The ability to drop CubeSat-sized surface payloads from a flyby spacecraft opens entirely new exploration capabilities. We focus on developing drop-off payloads for deployment onto the surface of a planet or moon with an atmosphere. These surface probes would need to survive high-velocity (2-5 km/s) entry. Reentry of spacecraft components namely flight recorders through the Earth's atmosphere have been shown by the Aerospace Corporation using the ReEntry Breakup Recorder (REBR) platform. Our application is towards safely landing an entire 6U, 36 cm × 24 cm × 12 cm CubeSat. Our proposed technology consists of an inflatable entry system that has a low-ballistic coefficient and is of low-cost and low-complexity. The technology can be a pathway towards testing larger landing platforms. The inflatable entry system contains multiple redundant bladders (cells) made of Vectran®, where even if one or a few are damaged, the system can maintain its shape. The bags are inflated using a solid-state chemical generator to produce nitrogen. The layers are hardened using a heat curing resin. The entry system will be slowed down using a subsonic parachute and crumple upon impact and absorb the brunt of the impact energy. In this paper, we perform a preliminary trade study and analyze both the challenges and opportunities with the proposed inflatable EDL system.

INTRODUCTION

The rapid miniaturization of electronics, sensors and actuators has resulted in development of new low-cost architectures for spacecraft such as CalPoly's CubeSat standard. Initially, CubeSats were intended exclusively for use in Low Earth Orbit (LEO). However, recent opportunities such as the SLS EM1 and Space Flight's Sherpa hosted platform open the door to interplanetary CubeSats[10,11,12]. These early interplanetary CubeSat designs will perform flybys and orbiting mis-

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sions. Some of these satellites are focused on science missions. The next logical step is towards development of surface landers. One promising approach is to land networks of small surface landers that provided detailed observations of many locations on Mars all at once[7,13]. Flagship Mars missions, such as Mars 2020, may offer the opportunity for ride-along CubeSat payloads to be delivered to the Martian surface. On the precursor to Mars 2020, the Mars Science Laboratory (MSL), there was nearly 110 kg of tungsten ballast that was dropped upon entry into the Mars atmosphere. Some of this ballast mass maybe repurposed as secondary CubeSat payloads. To minimize risk on the primary mission, it is important for the secondary CubeSat payload to separate well before the primary mission's Entry, Descent and Landing (EDL) sequence. However, this requires an independent EDL system for the secondary payload.

EDL through the Martian atmosphere or for that matter other bodies with a thin atmosphere presents an important challenge. Before entry, a spacecraft maybe reentering at 4-5 km/s and it needs to use the atmospheric drag to slowdown. Even with the thin atmosphere of Mars, the entry vehicles will heat up to more than a 1000 K. An additional important challenge with the Martian atmosphere is the expected variability with increasing or decreasing pressure due to seasons and surface weather. The entry vehicle needs to slowdown, withstand the entry force and high-temperature and reach a low enough altitude to deploy subsonic parachutes. Various techniques have been demonstrated for landing on the surface, including powered landing using retrorockets on the Viking mission, use of inflatables to bounce and cushion the hard landing as with the Pathfinder and Mars Exploration Rover (MER) missions[4], and use of the skycrane rocket assisted landing as with MSL.

A critical device for atmospheric entry is an aeroshell. Aeroshells have been miniaturized and successfully flown by the Aerospace Corporation for their Re-Entry Break Recorder (REBR) Platform[9]. These devices have successfully reentered through the earth's atmosphere and radioed the contents of a data recorder before landing into the ocean. REBR is relatively simple and elegant design that contains heat ablating materials and a foam core to protect the payload from entry shock and vibration. A modified REBR, called MarsDrop has been proposed by NASA JPL for deploying a small lander on Mars[5]. In addition, Georgia Tech's RED-Data2 is another small lander based on the REBR design[8].

Our approach is to demonstrate an inflatable aeroshell that contains many redundant bladders protected by an outer heating ablating material. The concept is called the Mars Inflatable Entry system for CubeSats (MIEC). MIEC has an inflatable, conical, aeroshell that would reduce the ballistic coefficient but take up much less mass and volume than conventional aeroshells. The internals would inflate with nitrogen gas and foam, and then harden to form an internal structure comparable to REBR. The hardening process involves curing of the resin foam. The outer layer, much like REBR, would contain a heat ablating material. The advantage of the inflatable entry aeroshell is that it can be made compact and be fully packaged into the CubeSat deployment standard. It would deploy into a cone several hours before entry, attain the desired shape and be set. In theory, the entry vehicle is modular and can be enlarged for large payload landings on Mars[1]. Inflatable hypersonic decelerators have been proposed for landing large payloads on Mars but uses conventional technology for the aeroshell[3]. In the next section, we present details of the proposed concept, a concept of operations, followed by comparison with previous Mars entry systems and preliminary CFD analysis. This is followed by discussions, conclusions and future work.

SYSTEM OVERVIEW

The MIEC inflatable entry vehicle concept for CubeSats is shown in Figure 1. We envision an entry capsule with a 0.90 m diameter and a mass of 24 kg that contains a core payload of 2 × 6U CubeSats. The vehicle will be in a hyperbolic trajectory with an entry speed of 7 km/s upon entering Mars.

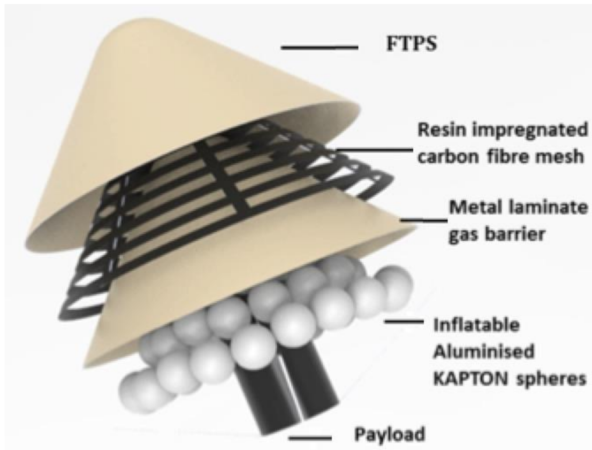


Figure 1: 3D Model of the Mars Inflatable Entry system for CubeSats (MIEC).

For this 24 kg capsule, we first consider a parachute to decelerate it to a touchdown velocity of 7 m/s. That would require a large, 40 m parachute. When including the mass of the parachute stowed in the capsule for this entry phase, the ballistic coefficient substantially increases, thus making the entry terminal velocity unattractive because it's in the supersonic regime. To date, a supersonic parachute has not been successfully demonstrated yet.

Another option is to have a 7 m wide parachute that slows down our 24 kg capsule to an impact/terminal velocity of about 15 m/s. This terminal velocity would still lead to a hard impact and hence requires an airbag system that would inflate and absorb the final touchdown. The airbag system may be similar to Mars Pathfinder airbags, as there is prior experience on airbag system use on Mars[4]. Use of airbags provide a credible strategy for landing small payload and requires further analysis.

A third alternative would utilize propulsion to slow-down the capsule until touchdown. This is using a retro-rocket landing system. The retro-rockets would provide 110 N thrust for 10-20 minutes. Such a system could be feasible using solid rockets, as the system is simple, has long shelf-life, has minimal risk during transit and has been shown feasible. However, there are important constraints on the storage of the propulsion system, particularly to keep it within storage temperature and to ensure upon ignition the temperature does not melt the surrounding structure. There is always a risk when igniting a rocket system after prolonged storage. A third challenge is throttling of the solid rocket. Throttling of the solid rocket is critical due to variability in atmosphere density and, thus, altitude attained before the rockets are fired. If the altitude is too high, the rocket needs to provide lower thrust and if it achieves lower altitude, then it needs to provide higher thrust.

We focus our presentation here on a fourth design option that utilizes the Mars atmosphere to slowdown and land using a combination of inflatable aeroshell, subsonic parachutes and finally landing inflatables to make a hard landing. Staging a 12U CubeSat into two separate 6U CubeSat, namely an Entry Phase 6U CubeSat and a Payload 6U CubeSat offers an alternative option for landing the payload on Mars. The expendable stage includes an Entry Phase CubeSat and the aeroshell with inflatables. The Entry Phase CubeSat will contain the Guidance, Navigation and Control electronics and batteries that feed power to heaters for aeroshell rigidization and inflation, ADCS unit and a flight electronics. A 5.8 m wide parachute will deploy from the 20 kg Payload CubeSat and decrease its velocity to 5 m/s before landing. The chassis will contain a shock absorbing structure to handle the hard landing.

Due to the small size of the CubeSat components, it is highly probable that they will be able to bear landing loads of 20g. Nevertheless, a detailed analysis of the impact will need to be performed. Additionally, we assume that the jettisoning of the Entry Phase CubeSat can be done with high reliability. Our preliminary studies suggest this inflatable entry vehicle maybe competitive with the conventional rigid entry vehicle systems.

CONCEPT OF OPERATIONS

We assume the CubeSat will be deployed with a certain velocity that will ensure undocking from the orbiter (Figure 2). MIRC will initially be contained with a 27U box and it will deploy down its four lateral faces and will unlatch from the entry capsule by burning the pyrotechnic fasteners that keep it tied to the bottom lid of the container.

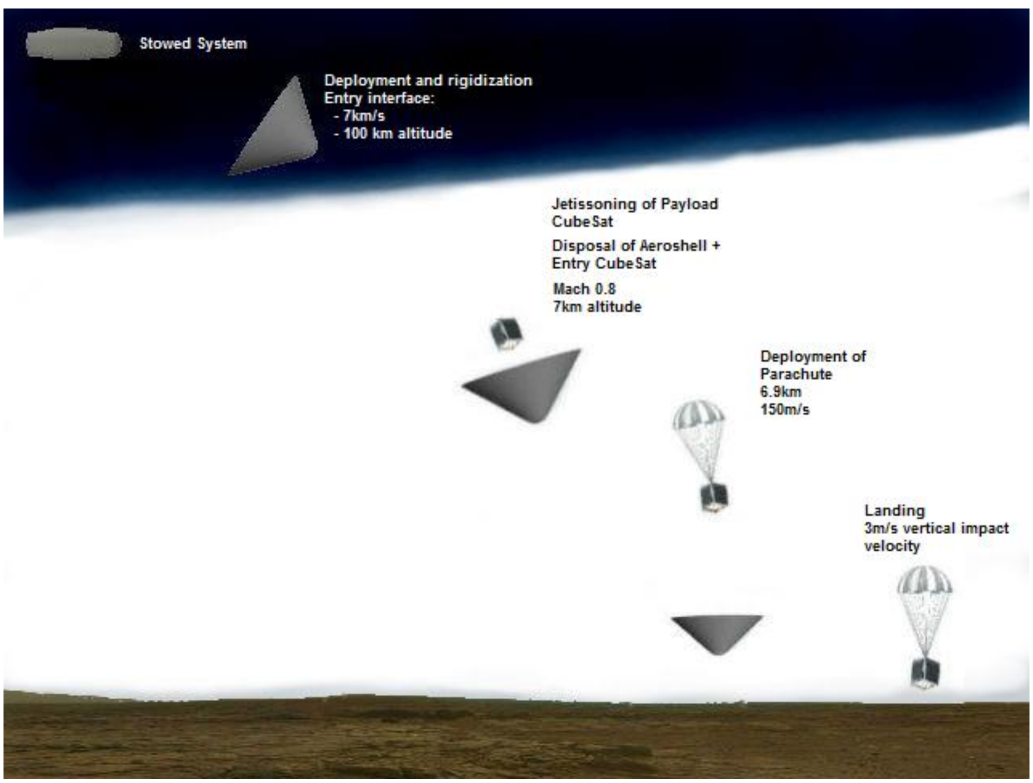


Figure 2: MIRC Concept of Operations

* Inflatables have their own battery for ignition system

At this stage, our entry vehicle will consist of the two 6U CubeSats with a Flexible Thermal Protection system folded around it. All the Vectran® inflatables will be deflated and held between the FTPS and the CubeSat by a semi-elastic Nylon® net latched to both the thermal protector and the chassis.

Inflation and Rigidization

The MIEC entry vehicle separates from the host vehicle and achieves at least a 50 meters separation, 8 hours prior to EDL. The entry vehicle then triggers the inflation of the aeroshell. The spherical Vectran® bladders will start inflating using a solid-state nitrogen gas generator and foam material. The foam material then hardens through heat curing using internal heaters. The system will have active volume control. Active volume control enables the entry vehicle to mitigate damage from one or more bladder failure by commanding adjacent bladders to increase their volume and compensate for the defective inflatable bladder. Importantly, our entry vehicle architecture is modular. By adding more of these inflatable units or increasing their size, the vehicle may be enlarged to take even larger entry payloads. This enables small capsules like ours to provide continuity and operational heritage to larger entry vehicles. The inflatables would achieve 4.5 kPa as demonstrated by Mars Pathfinder airbags and be made of multiple layers of Vectran®.

The bladders will form a conical pyramid. Above the inflatables will be a rigidizable layer that contain carbon fiber weave with a 0/90/0 configuration impregnated with thermally cured resin. With this component, we will be able to rigidize the aeroshell with embedded resistive heaters that will provide localized thermal control. The outer layer of the entry vehicle will consists of rigid FTPS and be covered in a heat ablation layer.

Atmospheric Entry

We expect our vehicle to perform fine maneuvers as its performing atmospheric entry. A GNC unit is required to achieve stable flight and avoid tumbling. This will be achieved by having the spacecraft spin at a sufficient angular velocity to provide stable flight through the atmosphere. Based on analysis of similar entry capsules, the terminal velocity of the entry vehicle would be reached at about 70 km altitude and will be in subsonic regime (approximately Mach 0.8). At that point, the jettisoning of the payload CubeSats will occur, and subsequently the 5.8 m wide parachute will deploy and decrease the CubeSat velocity to about 5 m/s.

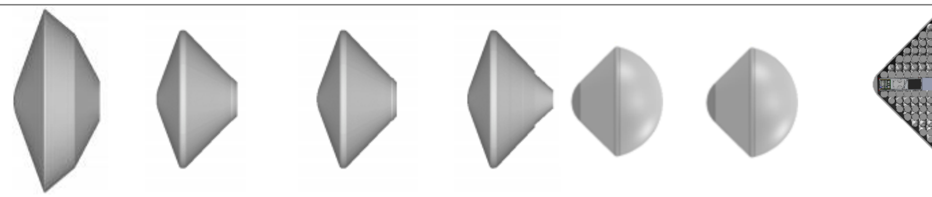
Landing

A first demonstration will be to prove successful landing of a CubeSat onto the Martian surface. The landing site will be on flat, sandy terrain. This avoids having to perform any complex corrections during final stages of landing. As with the MER and MSL, the entry vehicle would transmit a tone via UHF while performing its landing maneuver. This will provide ground control the ability to trace problems as the vehicle is entering the Martian atmosphere.

Comparison with Other Entry Vehicles

Table 1 shows a comparison between some of the entry vehicles. Viking, Pathfinder, MER and Phoenix all have heavy payloads that are several hundred kilograms. In comparison, MIRC is 20-folds smaller. On the other end of the spectrum, are REBR and JPL’s MarsDrop. Both would be less than 5 kg. MIRC would need to be 24 kg, with a 16 kg payload and 8 kg entry system. The ballistic coefficient is low enough that MIRC can attain subsonic terminal velocities and reduced temperature build-up comparable to JPL’s MarsDrop. As with all other entry vehicles compared, MIRC will utilize spin to achieve attitude control and stability.

Table 1: Mars entry vehicle comparison[2].

	Viking	Pathfinder	MER	Phoenix	MarsDrop	REBR	MIRC
							
Diameter (m)	3.5	2.65	2.65	2.65	0.3	0.3	0.9
Entry mass (kg)	930	585	840	602	2.8	4	24
Relative Entry Velocity (km/s)	4.5	7.6	5.5	5.5	7-7.5	10	7*
Relative Entry FPA (deg)	-17.6	-13.8	-11.5	-13.2	-13.25	-13.25	-13*
$m/(C_DA)$ (kg/m^2)	64	62	90	65	39.61	56.59	45.3
Stability Control	Spin	Spin	Spin	Spin	Spin	Spin	Spin

SIMULATIONS

A simulation of the proposed conical design for the inflatable lander was carried out with the open source computational fluid dynamics (CFD) software, OpenFOAM. Preliminary results were obtained, but there are important modeling discrepancies that need to be addressed. Validation studies of these solvers for hypersonic flows have been performed and showed good agreement with experiment and common commercial solvers for hypersonic flow[6].

For these preliminary CFD studies, we chose to simulate the vehicle at relatively low hypersonic speeds and altitudes with simplified governing equations and models. The free-stream conditions for a Mars entry vehicle were determined from the data collected during the Mars Pathfinder Mission[3]. The static temperature and pressure were chosen to be 150 K and 10 Pascals respectively, which correspond to altitude of around 40 km. The gas was assumed to be CO_2 with thermodynamic properties at 150 K. The free-stream velocity was estimated to be 2,000 m/s or a Mach number of 10.5. The flow was assumed inviscid so the compressible Navier-Stokes equations simplify to the Euler equations. The 3-D model and grid mesh model for a 40 degree angle of attack is shown in Figure 3.

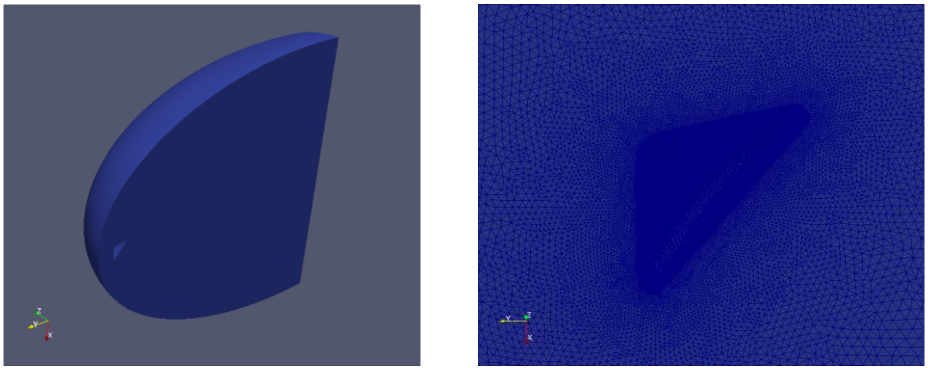


Figure 3: Computational domain and mesh of the aeroshell at 40 deg angle of attack.

The results are shown in Figure 4. They show filled contours of velocity, temperature, pressure and density at an angle of attack of 40 degrees. They display many of the defining characteristics of hypersonic flow over a blunt body, such as the bow shock and low pressure separation region behind the vehicles. The maximum temperatures are reached just behind the bow shock at about 2000 K. But there are major errors in the solution caused by the instabilities. The most obvious error is the "lumpiness" of the bow shock. This instability is called the Carbuncle problem and is one of the major difficulties in accurately simulating hypersonic flow over blunt bodies.

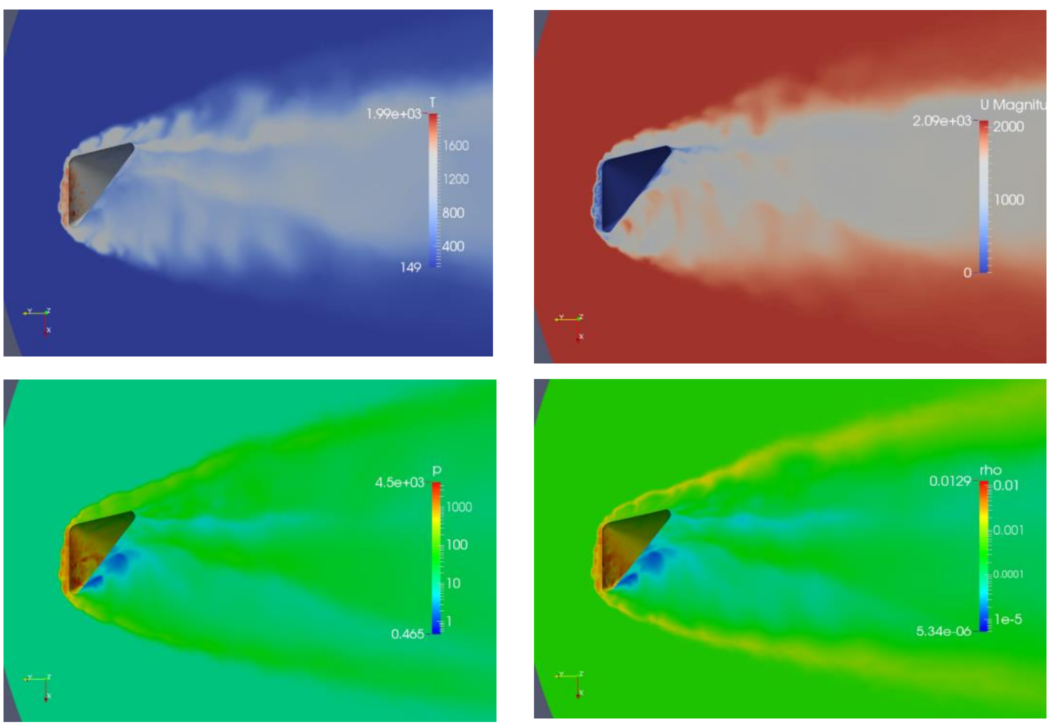


Figure 4: CFD simulation showing temperature (top left), velocity (top right), pressure (bottom left) and density contours (bottom right).

Figure 5 shows how lift and drag characteristics vary with angle of attack. It is notable that lift coefficient is negative at positive angles of attack. L/D ratio is also a maximum at very high angles of attack. This is going to cause asymmetric heating and so special considerations for TPS will have to be made.

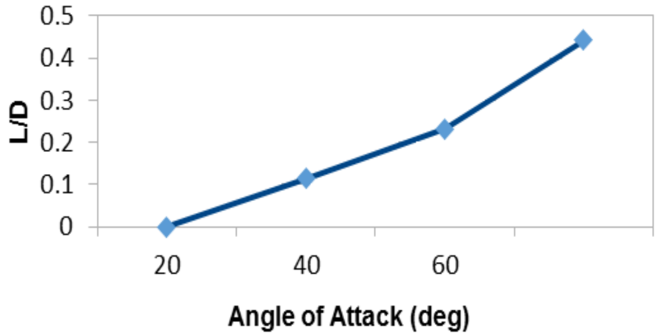


Figure 5: L/D vs Angle of Attack

Our preliminary simulation results were sufficient in determining some simple aerodynamic coefficients and have given clear direction for future work. First, the Carbuncle problem evident in the flow field needs to be solved. Next, viscous terms with appropriate turbulence modeling should be implemented. This should allow more accurate heat transfer estimates due to boundary layer modeling and to help address the carbuncle problem due to flow viscosity. Better flow initialization strategies need to be determined. A trajectory analysis has to be performed as well, obtaining more accurate values of terminal velocity and schedule of entry/descent phase. So far, these values are just estimates based on other entry capsules as MarsDrop[5]. We believe that if this mission were to fail, it will not pose a threat to the primary mission.

CONCLUSION

The hundreds of kilograms of ballast available on Mars flagship missions, such as Mars Science Laboratory (MSL) and Mars 2020, present a potential opportunity to carry CubeSats. These CubeSat may be used to perform technical demonstration or short, focused science exploration missions. To minimize risk to the primary mission, it is critical for the secondary CubeSat payloads to separate well before Entry, Descent and Landing (EDL) and use its own EDL system to land on Mars. An EDL module for CubeSats can readily transform them into surface landers to explore the Martian surface. In this work, we analyze the preliminary feasibility of using a 24 kg inflatable entry vehicle architecture that uses dozens of inflatable bladders to attain a conical shape. The vehicle would carry two 6U CubeSats, 8 kg each. The inflated conical shape would be rigidized using foam. The entry vehicle would be comparable in terms of its internal structure to Aerospace Corporation's REBR platform, but would attain subsonic terminal velocity. This simplifies the challenges of guidance, navigation and control. The technology can be a pathway towards testing larger human landing platforms on Mars.

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