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Technology Overview and Assessment for Small-Scale EDL Systems

Casey R. Heidrich[1], Brandon P. Smith[2], and Robert. D. Braun[3]

[1] Georgia Institute of Technology, Space Systems Design Laboratory (crheidrich@gatech.edu), [2] NASA Ames Research Center (brandon.p.smith@nasa.gov), [3] Georgia Institute of Technology (robert.braun@ae.gatech.edu)

Abstract

Motivated by missions to land large rovers and humans at Mars and other bodies, high-mass EDL technologies are a prevalent trend in the research community. In contrast, EDL systems for low-mass payloads have attracted less attention. Significant potential in science and discovery exists in small-scale EDL systems. Payloads acting secondary to a flagship mission are a currently under-utilized resource. Before taking advantage of these opportunities, further development of scaled EDL technologies is required. The key limitations identified in this study are compact decelerators and deformable impact systems. Current technologies may enable rough landing of small payloads, with moderate restrictions in packaging volume. Utilization of passive descent and landing stages will greatly increase the applicability of small systems, allowing for vehicles robust to entry environment uncertainties. These architectures will provide an efficient means of achieving science and support objectives while reducing cost and risk margins of a parent mission.

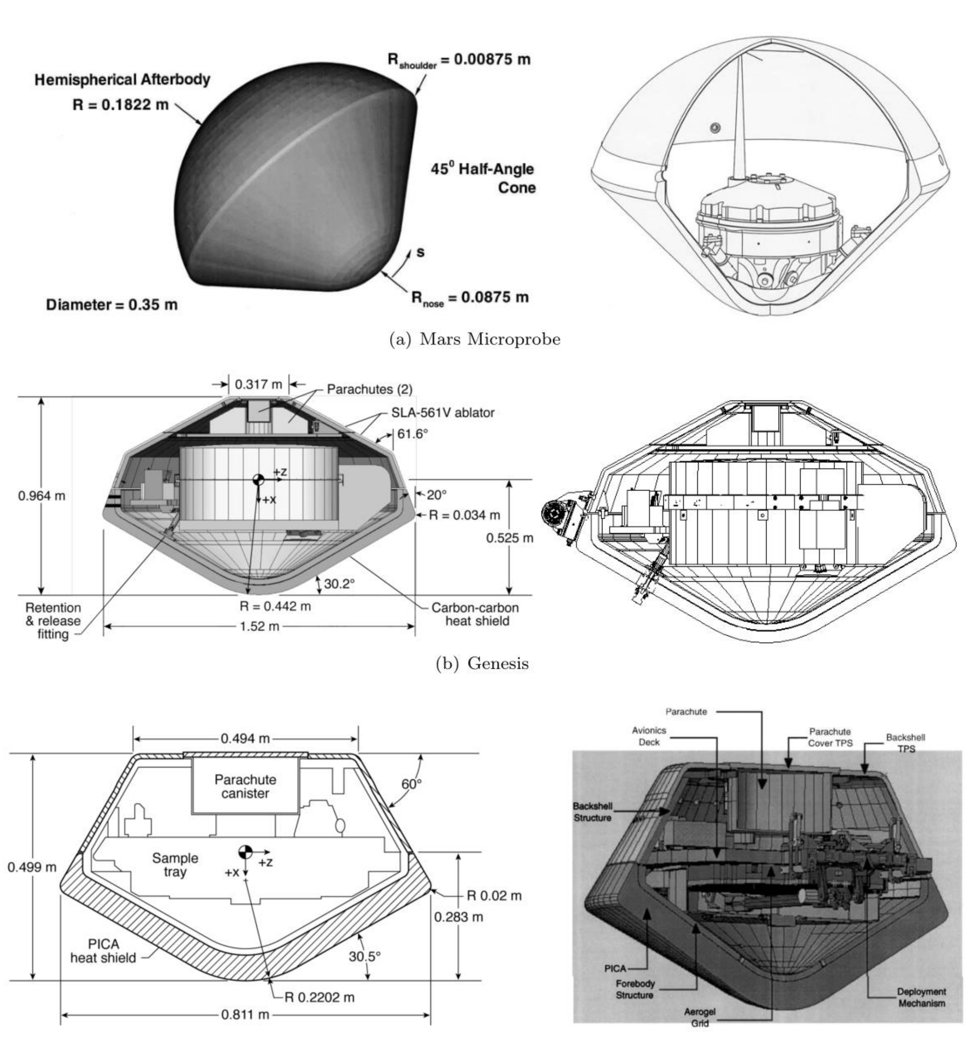
Motivation

The movement toward flying smaller spacecraft emerged out of academia through strict enforcement of mass and volume limitations and by defining standard mechanical and electrical interfaces. In recent years, NASA has begun to actively integrate small spacecraft into its mission portfolio and is reaping the benefits. The value proposition posed by small spacecraft is high due to their dramatically lower cost and more forgiving risk posture compared with large, "traditional" spacecraft with payload-driven requirements. The vision of the current research is to apply the tenets of the small spacecraft movement toward an EDL system for secondary payload missions. An EDL capability for small spacecraft would enable scientists to recover payloads from Earth orbit as well as broaden the reach of small spacecraft to landing on other celestial bodies with substantial atmospheres (e.g. Mars, Venus, and Titan).

Small-scale EDL technologies will create novel opportunities for science and exploration objectives. A flagship mission first entering orbit, particularly by aerocapture means, could release small probes to provide day-of atmospheric data before entry of the main vehicle. Data could be processed in-situ or transmitted to Earth as a means of increasing mission success rates. A larger geographical region may be covered with multiple probes released on the approach trajectory. A large variety of missions become feasible with development of compact and passive entry vehicles.

Mission opportunities for small entry vehicles include:
- LEO reentry of long-term science objectives
- ISS rapid return of science or medical material
- Mars sample return missions
- A priori EDL environment measurements
- Multiple science probes for redundancy/greater ground coverage

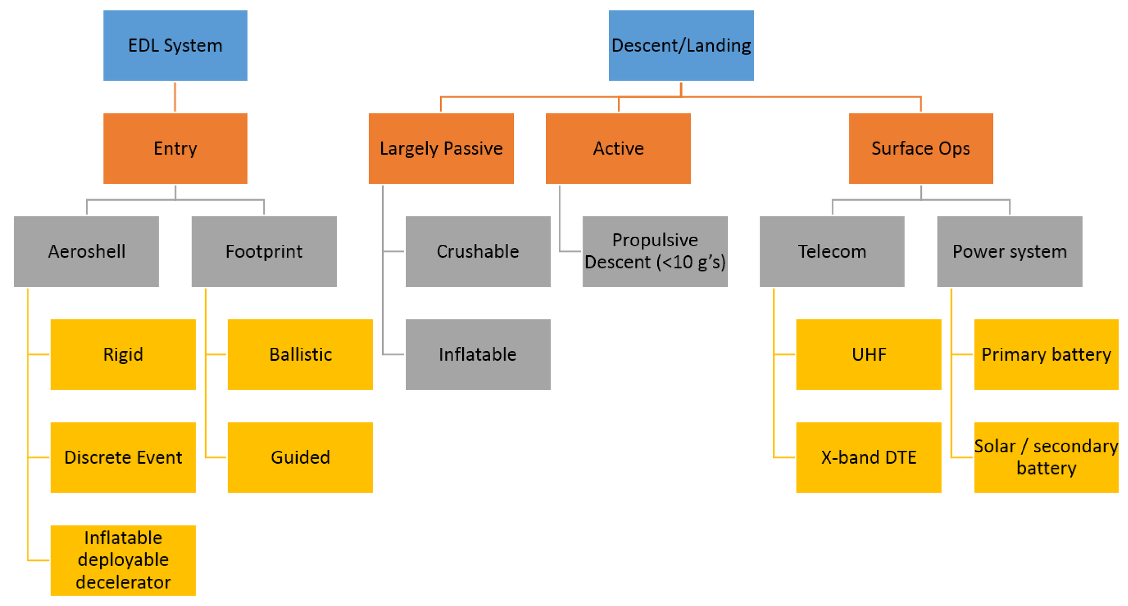
Historical Perspective



Mission	Mars Microprobe	Genesis	Stardust
Launch Year	1999	2001	1999
Planet	Mars	Earth	Earth
Forebody Geometry	45-deg sphere-cone	70-deg sphere-cone	60-deg sphere-cone
Aftbody Geometry	Hemisphere	Biconic	Truncated cone
Aeroshell Diameter	0.35 m	1.5 m	0.8 m
Thermal Protection	SIRCA	CCA/Insulator	PICA
Entry Mass	3.84 kg	205.6 kg	45.6 kg
Ballistic Coefficient	38 kg/m^2	90 kg/m^2	70 kg/m^2
Descent System	None	Parachutes (2)	Drogue/Main Parachute
Impact System	Structural	None	Structural
Entry Velocity	6.90 km/s	11.0 km/s	12.9 km/s
Entry FPA	-13.25 deg	-8.0 deg	-8.2 deg

Historical data on design of small reentry probes. Common design factors include a rigid sphere-cone outer mold line (OML), "stacked" packaging techniques, and static hardware. Providing a soft landing required two deployable deceleration systems (Stardust) or more complicated schemes such as mid-air retrieval (Genesis – failed deployment).

Design Space



Design tree for small EDL architectures. The heritage EDL design paradigm may be ineffective or even infeasible on small scales. In order to fully take advantage of smaller reentry vehicles, it is advantageous to reexamine typical entry architectures utilizing a separate hypersonic entry system, decelerator, and landing system. From this, two particularly important ideas with respect to the small-scale EDL design process were conceived. First, cross-utilization of systems may be key for achieving small EDL without significantly altering mission requirements such as landing g's and timeline margins. Second, complete removal of systems may be necessary to achieve feasibility. This may drive mission requirements when small vehicles lack the capacity for controlled flight or soft landing.

Technology Assessment

Concepts suitable for small-scale EDL applications were taken from literature and compared using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

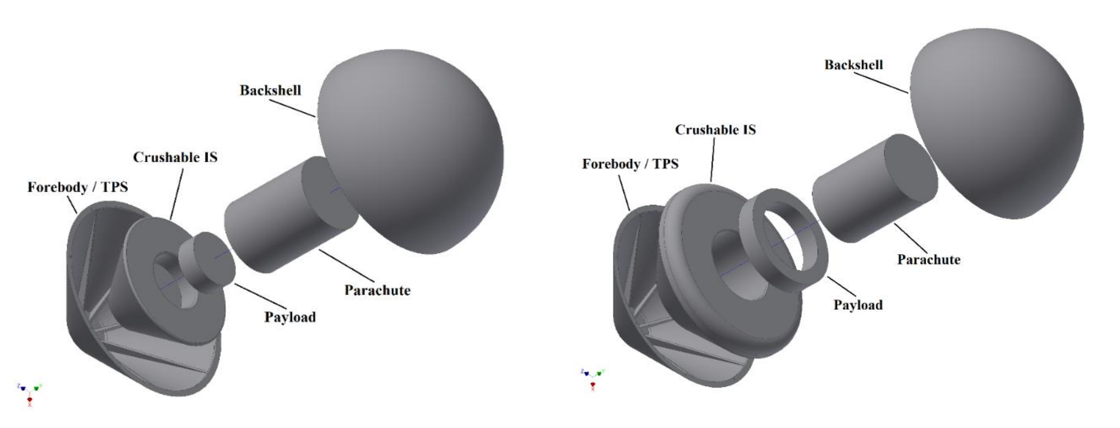
Descent System	Deceleration	Mass	EDL Timeline	Scaling	Weighted Total
Parafoil	5	2	2	3	2.7
Auto-rotor	3	2	2	3	2.4
Drag Ribbon	3	4	4	4	3.8
Propulsive	4	1	3	2	2.3
None	1	5	5	3	3.9

Descent system assessment for small-scale vehicles. Two viable options are the drag ribbon concept and no decelerator concept (typical of a penetrator). The drag ribbon concept consists of a long ribbon released behind the vehicle designed to create drag due to its inherent tendency to flap in the oncoming flow.

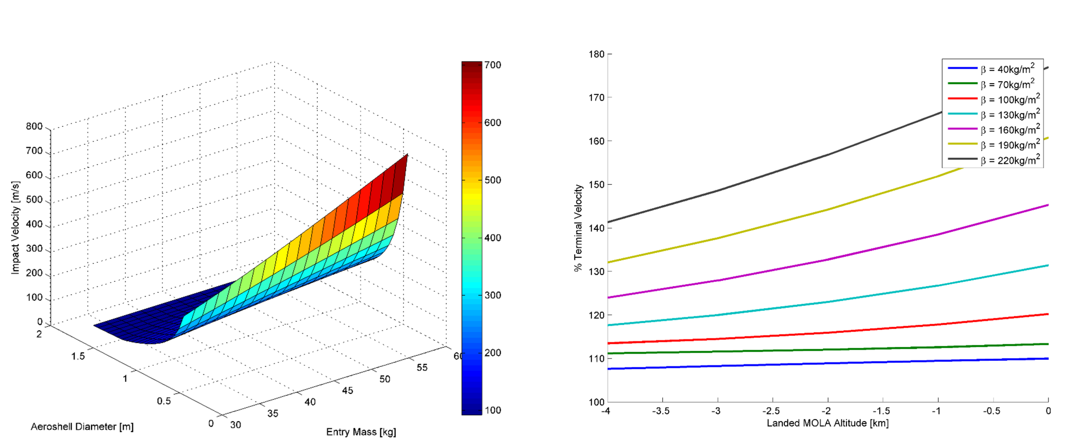
Landing System	Impact g's	Complexity	Volume Efficiency	Scaling	Weighted Total
Deployable Legs	3	3	3	4	3.1
Airbags	4	2	3	2	2.8
Crushable Structure	2	4	2	5	3.0
Shell Lander	3	2	2	4	2.5
Penetrator	1	3	4	4	2.9

Landing system assessment for small-scale vehicles. Results lack any clear candidate. Soft landing presents a significant challenge on small scales. The crushable structure option is a viable for future research due to its inherent simplicity and passive utility.

Challenges



Packaging in restricted OML geometries. Small-scale EDL systems impose strict volume requirements. Reexamination of the typical "stacked" technique (left) may provide opportunities for volumetric efficiency. For example, the toroidal configuration (right) accommodates the payload length around the parachute canister.

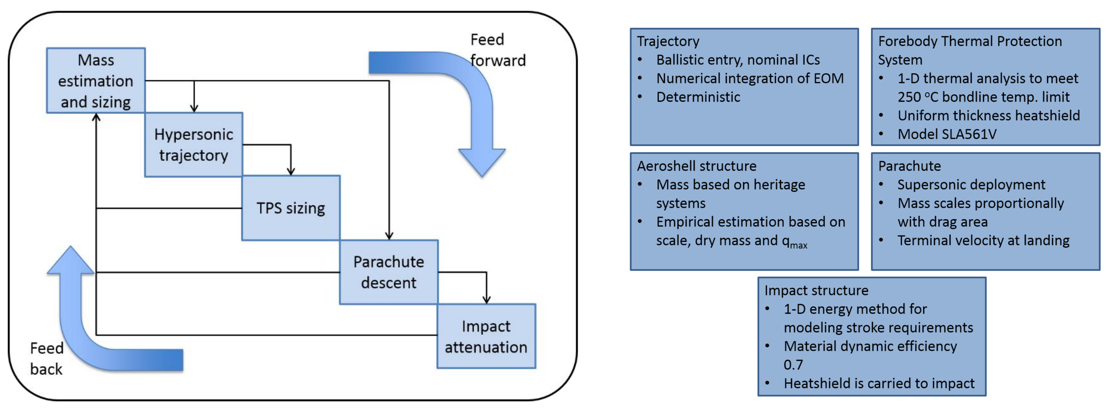


Impact conditions (at Mars) and vehicle properties. Moderate changes in vehicle mass and size properties greatly influence impact conditions absorbed by the landing system. Reducing the MOLA landed altitude reduces the impact velocity of high ballistic coefficient vehicles.

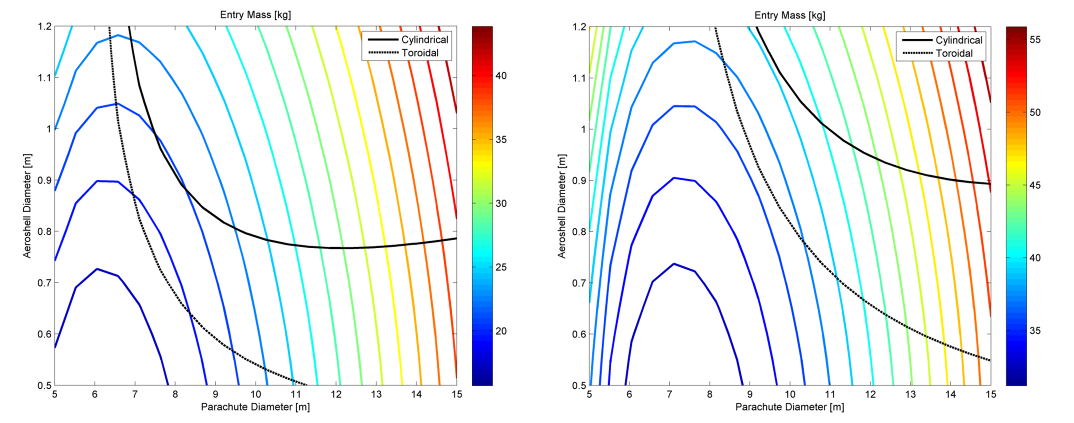
Mars Mission Design

A hypothetical Mars mission is proposed as an application of small-scale EDL. The mission is to land a static science payload carrying sensitive instruments on the Martian surface. The requirements are:

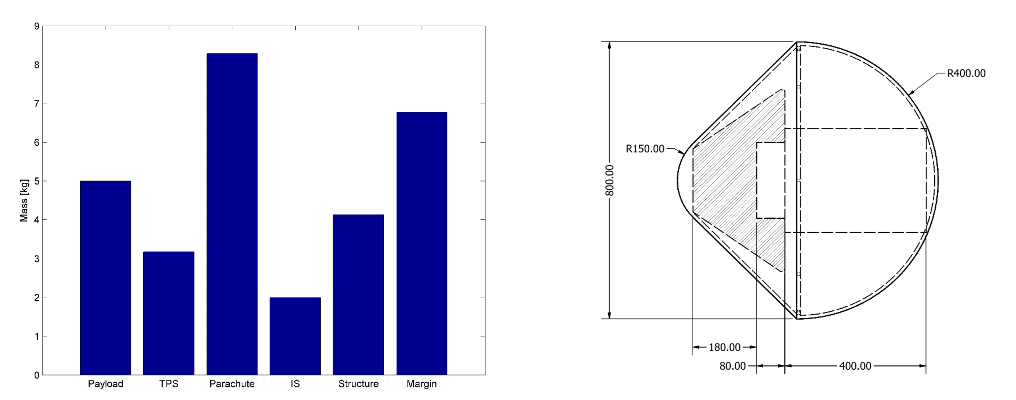
- The payload is 3U in volume.
- Restrictions on the primary vehicle limit capsule height to 0.8 m.
- The payload shall experience less than 12 g's (sustained).
- The bondline temperature shall not exceed 250 ºC
- The payload shall experience less than a 50 g landing impulse.



Design Structure Matrix for small passive lander. A single design iteration incorporates vehicle sizing, dynamics, and environment loads. The process is repeated until convergence.



Mass optimization and sizing limitations. Sizing contours are shown for a 3 kg (left) and 10 kg payload (right). The vehicle OML height represents the primary obstacle in selecting a mass-optimal design. Novel packaging techniques, such as the toroidal configuration, have the potential to greatly reduce total entry mass.



Final design subsystem breakdown. A solution consistent with sizing limitations and mission requirements was found. The parachute requires a significant mass fraction compared to heritage designs.

Conclusions

Maturation of small EDL technologies greatly increases our aptitude to return from space. Non-conventional science and exploration missions are likely to achieve fruition on a small-scale, affordable platform. The potential to piggyback existing missions as a passive secondary will push these possibilities closer to realization. This research outlined the potential design space for small EDL systems. Scalability and volume packaging constraints present a challenge for feasibility. A hypothetical Mars mission design indicated that minimum-mass configurations may be infeasible with current technologies due to packaging constraints.

Moving Forward

The next steps in this research must formulate atypical design architectures. For the descent stage, this includes developing compact parachute packaging techniques. Largely untested concepts present viable options for efficient volume utilization of the descent stage. In some cases, it may be necessary to completely eliminate the descent stage, with the landing system absorbing the remaining kinetic energy on impact. Cross-utilization of EDL systems also creates opportunities for volume optimization in the vehicle.

The sizing study found impact attenuation systems severely impact volume efficiency in small EDL systems. Landing systems require appreciable longitudinal space in the vehicle that scales poorly. A gap in current research on crushable structures makes application of this technology difficult. Further modeling and testing of deformable impact systems will allow for design of passive configurations robust to environment uncertainties.

Novel EDL design concepts, typically unacceptable for a high-mass architecture, present unique solutions to space limitations on small scales. The approach to take measured risk with small EDL systems makes application of low TRL systems more viable.

References

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