The Challenges of Landing on Mars

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Humans have been fascinated with the idea of exploring Mars since the very beginning of the space age. Largely due to the belief that life may have at one time existed in some form, surface exploration has been the ultimate ambition of this exploration. Unfortunately engineers and scientists discovered early on that landing a spacecraft on the surface of Mars was to become one of the most difficult and treacherous challenges of robotic space exploration. At arrival to Mars, a spacecraft will be traveling at velocities between 4 and 7 km/s. 100% of this kinetic energy (KE) must be safely removed for a lander to deliver its payload to the surface. Fortunately Mars has an atmosphere substantial enough to allow the combination of a high drag heatshield and a parachute to remove 99% and 0.98% respectively of this kinetic energy. Unfortunately the atmosphere is not substantial enough to bring a lander to a safe touchdown. This means that an additional landing system is required to remove the remaining kinetic energy. On all previous successful missions the landing system has consisted of 2 major elements, a propulsion subsystem to remove an additional 0.002% (~50 - 100 m/s) of the original KE and a final dedicated touchdown system. The first generation Mars landers used legs to accomplish touchdown. The second generation of Mars lander touchdown systems used airbags to mitigate the last few meters per second of residual velocity. NASA is currently developing a third generation landing system in an effort to reduce cost, mass and risk while simultaneously increasing performance as measured by payload fraction to the surface and accessible terrain roughness.

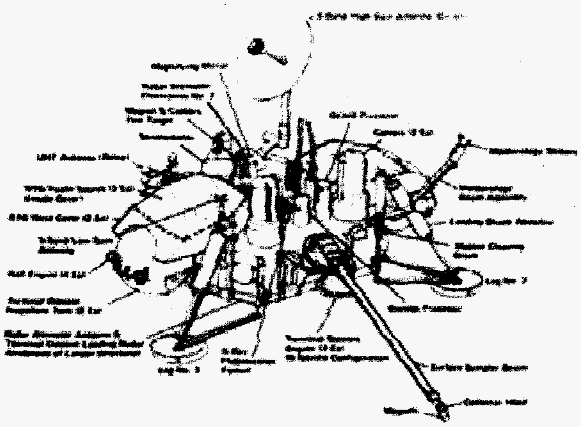

Figure 1: First generation landing system used on Viking lander which landed on Mars in 1976.

The Viking lander's legs represents the first generation landing system technology. The lunar Surveyor and the Apollo programs developed the basics of landing leg technology in the early 1960's. In conjunction with a variable thrust liquid propulsion system and a closed loop guidance and control system, legs represent a very elegant solution to the touchdown problem. They are simple, reliable mechanisms that can be added to an integrated structure which houses the scientific and engineering subsystems required for a typical surface mission. The key challenges with a legged system revolve around the fact that in order to make the lander safe for landing in regions with large rocks the legs must either be made long or the belly of the lander must be made very strong. Neither solution is attractive, resulting in either a top heavy lander incapable of landing on sloped terrain, or a significant amount of belly reinforcement carried along for the remote chance of incurring a direct rock strike. A second major challenge of the legged landing architecture is that of safe engine cut-off. In order to prevent the guidance and control system from inadvertently destabilizing the system while the lander is in the process of touching down, touchdown sensors are employed to shut down the propulsion system at first contact. This causes the lander to free-fall any remaining distance, which increases the touchdown kinetic energy which in turn reduces landing stability and increases structure mass.

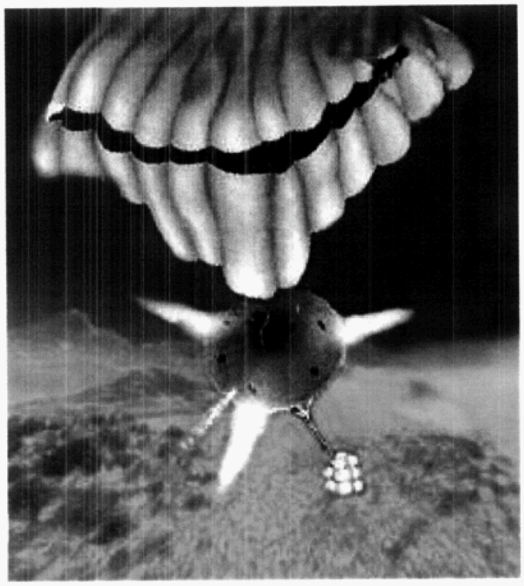

Figure 2: Second generation landing system used on Mars Pathfinder and MER landers.

The second generation landing system was developed for the Mars Pathfinder mission and subsequently improved upon for the Mars Exploration Rover (MER) missions. These systems use a combination of fixed thrust solid rocket motors and airbags to perform the touchdown task. Developed to reduce cost and improve landing robustness the airbag system is designed to provide omni directional protection of the payload while bouncing over rocks and other landing hazards. Since the system can also self right itself from any rest orientation the challenge of landing stability has been completely eliminated. Given that the lander comes to rest prior to self righting itself, the challenge of rock strikes has been reduced to that associated with the self righting event, which is significantly more benign. The challenge of thrust termination has not been removed completely but it has been decoupled from landing stability. Although the airbag landing system has addressed some of the challenges and limitations of legged landers, it has also introduced some challenges of its own. Horizontal velocity control using solid rockets and airbag testing were both significant development challenges for the Mars Pathfinder and MER missions.

Both the first and second generation landing systems pose one more major challenge to the safe delivery of rovers to the surface; rover egress. As Mars surface exploration matures, the use of rovers is becoming a more dominant factor in lander system design. The MER missions demonstrated the value of a fully functional rover that was not reliant on its lander to complete its surface mission. Future missions such as the 2009 Mars Science

Laboratory (MSL) are being developed to expand on the capabilities and size of roving systems. The Sojourner rover and the Spirit and Opportunity rovers all experienced their most difficult and threatening mobility condition as they made their way off of their landers. The third generation landing system being developed for the MSL mission is being designed to directly address all of the main challenges present in the first and second generation landing system while completely eliminating the challenge of egress. It is called the sky crane landing system.

The Skycrane Landing System (SLS) eliminates the use of a dedicated touchdown system by directly placing the rover onto the surface of Mars, wheels first. It does this by placing the propulsion subsystems above the rover, flying the joined system to within 20-30 meters of the surface, then using a tether system to lower the rover several meters below the propulsion system. The two body system then descends the final few meters wherein the rover is set onto the surface and cut away from the propulsion module. The propulsion module performs an autonomous fly-away maneuver and crash lands 500 to 1000 meters away. The SLS maximizes the use of its onboard guidance and control system and liquid propulsion system to reduce the velocity at touchdown to be within the design limit load of the rover as set by its roving requirements. The SLS also takes advantage of the fact that the rover's mobility system is inherently designed to interact with rough, sloping, natural terrain. The rover's loads and stability capabilities as dictated by its surface mission in conjunction

Figure 3: Third generation landing system being designed for use on the 2009 Mars Science Laboratory mission.

with the SLS delivery capabilities, results in an extremely robust landing system capable of delivering a large rover to rugged terrain.

Rovers are designed to simultaneously possess high ground clearance, high static stability, ruggedized belly-pans, and passive terrain adaptability/conformability. These are all the same features that could be used to describe the ideal touchdown system. The SLS is exploiting these inherent capabilities of its payload by eliminating the use of a dedicated touchdown system while simultaneously improving landing performance and eliminating the need to perform an additional high risk egress.

These system level performance improvements have been realized by rethinking the landing paradigm as opposed to inventing a new device or subsystem. All of subsystems required for the MSL mission are derivatives of existing commercial or aerospace technologies. The major challenge of the SLS is concept validation of this novel architecture. To this end NASA is currently in the process of identifying the most suitable development approach. Much of the development plan will focus on four primary area; 1) guidance and control transient and pendulum dynamics suppression during the Skycrane maneuver, 2) minimization of transient and pendulum dynamics via hardware design, 3) touchdown detection 4) rover touchdown dynamics and drive away capabilities.

As Mars explorers have discovered the hard way, it's typically not the fall that kills you it's the landing. Landing technology has matured significantly over the last 40 years since NASA started exploring extraterrestrial surfaces. Each successive generation of landing technology has attempted to resolve the challenges posed by the previous generation. The Skycrane landing system represents the latest evolution of landing technology.

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