AAS 13-236

Mars Science Laboratory Entry, Descent and Landing System Overview

Adam D. Steltzner[1], A. Miguel San Martin[2], Tomasso P. Rivellini[3], Allen Chen[4]
Jet Propulsion Laboratory. Pasadena Ca. 91109-8099

Abstract

The Mars Science Laboratory project recently places the Curiosity rove on the surface of Mars. With the success of the landing system, the performance envelope of entry, descent and landing capabilityies has been extended over the previous state of the art. This paper will present an overview to the MSL entry, descent and landing system design and preliminary flight performance results.

Introduction

On August 5th and 10:31 PM PDT, signals were received on earth confirming the successful landing of the Mars Science Laboratory's Curiosity rover on the planet Mars. With this signal came the first proof of success of the ambitious new entry descent and landing system that had taken Curiosity to the surface. Curiosity weighs over 900 kg and required the development of a new landing system. The MSL entry, descent and landing system is novel, using old technologies in a new application and pioneering new technologies as well.

EDL Overview

The entry, descent and landing process at Mars, or any other planet with an atmosphere, is a process of managed energy dissipation. The central challenge is to remove the kinetic energy of planetary arrival and prepare for a managed impact with the surface. At Mars,

---

[1] Phase Lead, EDL, System Engineering Division, JPL/MS321-637, AAS Member

[2] Deputy Phase Lead, EDL and GNC Chief Engineer, GNC Division, JPL/MS198-XXX, AAS Member

[3] Mechanical Systems Lead, EDL, Mechanical Engineering Division, JPL/MS321-230, AIAA Member

[4] Operations Lead, EDL, Systems Engineering Division, JPL/MS321-268, AAS Member

Copyright, 2012 by California Institute of Technology. Published by AIAA, Inc., with permission

where the atmosphere is roughly about 1/100th that of Earth, maintaining altitude and sufficient timeline to prepare for the surface contact is paramount. The job of dissipating arrival energy and preparing for managed impact is spread throughout the different segments of EDL.

Final Approach

During the Final Approach segment, at the end of the seven and a half month cruise to Mars, preparations for entry, descent, and landing became the focus for the spacecraft and flight team. These preparations center upon three primary objectives: 1) get the spacecraft ready for EDL, 2) get the spacecraft to the right place to start EDL at the right time, and 3) tell the spacecraft what it needs to know to execute EDL successfully.

These objectives result in activities such as hardware checkouts and parameter loads, trajectory correction maneuvers to put the vehicle on course for the targeted entry conditions, and navigated state updates to seed the entry system with accurate knowledge for use in guided entry. These activities require the cruise and EDL teams to work in concert to balance operational risks to the spacecraft in cruise with EDL risks associated with putting the vehicle in the best possible physical and software state to execute EDL successful.

Exoatmospheric Segment

The exoatmospheric segment of EDL span the period from cruise stage separation through arrival at the entry interface point, 3522.2 km from the center of Mars. During this period, the vehicle completes its transition from cruise to EDL configuration with the separation of the cruise stage at Entry – 10 minutes. At Entry-9 minutes, full EDL control of the spacecraft becomes active and the vehicle begins using reaction control thrusters to stop the residual spin rate from cruise and turn to the desire entry attitude. Two externally mounted tungsten masses, used to balance out the center of gravity during the spin stabilized cruise portion of the mission, are jettisoned, thus leaving the spacecraft with an offset center of gravity to generate lift during entry.

Entry

The entry segment of EDL spans approximately 4.5 minutes and begins at entry interface and ends at supersonic parachute deploy. At entry interface, the vehicle is traveling at approximately 5.8 km/s at a targeted flight path angle of -15.5°. At this point, the entry propulsion system transitions from blow-down pressurization to a higher regulated pressure to provide sufficient thrust for entry control and the later powered flight segment.

When the spacecraft senses drag acceleration of 0.2 Earth g's, entry guidance begins. Using the lift provided by the center of gravity offset, the guided entry system is able to correct for errors in initial delivery state, atmosphere conditions, and aerodynamic uncertainties while also significantly increasing altitude capability by modulating the direction of lift. If lower than anticipated atmospheric drag is encountered, either because of atmospheric density deviation from the expected atmosphere, or aerodynamic drag deficit from expectation, the vehicle flies to a lower altitude than the reference trajectory thereby increasing drag. If

Copyright, 2012 by California Institute of Technology. Published by AIAA, Inc., with permission

higher than expected drag is encountered, the vehicle lifts itself in the atmosphere. Nominally, the reference trajectory has the lift vector being stored in a predominately sideway direction, resulting in three bank reversals (think s-turns) being performed to keep the vehicle within the cross track error boundaries. The altitude and precision capabilities enabled by guided entry allowed the selection of never before considered landing sites on the Martian surface, sites that were far too cramped or too high to be considered previously.

This behavior used repurposed Apollo guidance algorithms to form a simple and robust guidance approach that allowed the reduction of landing miss distance from 70+ km down to under 10 km. The guidance scheme is broken into two different regimes. First, range control from entry interface down to approximately 1100 m/s, where the down track drag acceleration is matched to attempt to be over the desired target when the parachute deployment conditions are met. During this portion of flight, the vehicle experiences peak heating and peak deceleration.

The second part of guided entry is heading alignment, in which cross track errors that may have accumulated due to the bank reversals and other disturbances during range control are corrected. The spacecraft flies ~100 km downrange during heading alignment at a near constant altitude between 10 and 15 km. At the end of heading alignment, the vehicle transitions into the "Straighten Up and Fly Right" (SUFR) maneuver, which rolls the spacecraft while separating balance masses to change the center of gravity of the vehicle in preparation for parachute deploy.

Figure 1: (left) Cruise Balance Masses being ejected from entry vehicle just prior to atmospheric entry. (Right) Entry balance masses being ejected just prior to parachute deployment.

The six tungsten masses used to create the CG offset needed for guided entry are ejected one at a time so as to reduce the spacecraft's angle of attack down to zero (fig. 1) degrees. This is done to avoid large swinging pendulum-like motion and subsequent high angular rates when the parachute opens.

Parachute Descent

Once the capsule has slowed its speed to approximately 400 m/s (Mach 1.7), a parachute is deployed. This parachute represents the largest extraterrestrial parachute ever flown. It is also the largest supersonic parachute ever used. The Viking design disk-gap-band

Copyright, 2012 by California Institute of Technology. Published by AIAA, Inc., with permission

parachute, developed by Pioneer Aerospace, slows the capsule, initially at 6 Earth g's. At a speed around 150 m/s (Mach 0.7) the heat shield of the capsule is released and allowed to fall away. Heat shield separation is very important, since altitude knowledge error can be as large as +/- 3km at this point; this is not close to accurate enough to allow landing without directly sensing the ground. Once this has occurred, a JPL built six-beam Ka-band pulse-pair Doppler radar is used to look for the surface and perform range and velocimetry measurements. These measurements are used to determine the next transition in vehicle flight configuration. At and altitude of 3000 m, the Mars Lander Engines (MLEs) on the Descent Stage are primed in preparation for backshell separation and Powered Flight.

Figure 2. Separation from the backshell and initiation of powered descent

Powered Descent

At a height of about 1600 m above the Martian surface while travelling around 85 m/s almost vertically downward, the spacecraft separates from the backshell and parachute and begins powered descent (figure 2). The triggering of the backshell separation event is based on the vehicle's velocity and altitude and takes into account the amount of time required to complete the backhsell separation events. Using 8 throttle-able hydrazine engines, with a resurrected Viking catalyst bed design by Aerojet Corp, the spacecraft diverts 300 m perpendicular to the plane of the entry trajectory to avoid the parachute/backshell and flies a profile to cancel the horizontal velocity and bring the vertical velocity to a specified value nominally ~240 m above the surface.

Once the vehicle has been delivered to a steady vertical descent flight condition at ~240 m above the eventual touchdown site, the vehicle nominally flies through the "constant velocity accordion," descending vertically for approximately 100 m. During the constant velocity accordion, nominally 100 m in size, a speed of 32 m/s is maintained until about 140

Copyright, 2012 by California Institute of Technology. Published by AIAA, Inc., with permission

m above the surface. The constant velocity accordion is to protect against altitude estimate errors by the vehicle during parachute descent where the radar beams may not be pointing at the final touchdown site and therefore not measuring the altitude to the final touchdown site. At ~140 m above the final touchdown site, the vehicle then decelerates at about 8 m/s^2 for about 115 m to a velocity condition of 0.75 m/s. The vehicle then throttles down four of the eight engines and prepares for the skycrane maneuver

Skycrane

At approximately 21 m above the landing site, the spacecraft begins the "skycrane" maneuver. The maneuver begins when the rover is separated from the descent stage, which contains the propulsion system and GNC sensors (IMU and radar), and is lowered below on a 7.5 m bridle system. During the deployment of the rover, the descent stage continues its 0.75 m/s trajectory vertically downwards toward the surface. During deployment, the mobility system is also released from its stowed condition. Once fully deployed at the end of the bridles, with the mobility released and ready to touchdown, the rover and descent stage continue downward at 0.75 m/s until contact with the Martian surface occurs. There is another portion of constant vertical flight at this stage, called the "ready for touchdown" accordion nominally of 5 m in length. This accordion exists, again, to compensate for possible range errors by the radar used in the planning of the skycrane timing. After the rover has touched down, the descent stage continues downward until persistent reduced throttle settings have been confirmed using a 1.5 second rolling window. At that time, touchdown is declared and flyaway begins.

Flyaway

After touchdown is declared, descent stage motion is stopped and the bridles are cut free. Control is transferred to the Descent Stage. The Flyaway controller on the Descent Stage executes an attitude and throttle profiles to fly it on a preprogrammed trajectory to a distance of at least 150. This leaves the rover wheels down on the surface of Mars and ready to begin commissioning.

Preliminary Flight Performance

The performance of the EDL system in flight was largely within the expectation of preflight predictions. Table 1 shows the as flown values for many of the quantities of interest.

Description	Average Prediction	Range of Prediction	As Flown Value
Peak Heating, Best Estimate (W/cm2)	TBD	TBD	TBD
Peak Pressure (atm)	0.315	0.301 – 0.331	0.305
Peak Deceleration (g's)	12.71	12.26 – 13.25	12.61
Number of Banks Reversals	3	2 -4	3
Parachute Deployment Mach	1.70	1.55 – 1.87	1.75
Parachute Deployment Dynamic Pressure (Pa)	494.9	431.7 – 564.8	493.6

Copyright, 2012 by California Institute of Technology. Published by AIAA, Inc., with permission

Peak Parachute Deceleration (g's)	6.69	5.34 – 8.37	6.07
Heat Shield Separation Mach	0.7?	0.05	?
Radar Lock-up Altitude (km)	6.82	5.71 – 7.64	8.35
Navigation Filter Velocity Error at Radar Lock-up (m/s)	N/A	N/A	0.76
Navigation Filter Altitude Error at Radar Lock-up (m/s)	N/A	N/A	113
Propulsion System Priming Time (sec)	17.9	13.9 – 23.8	17.3
Backshell Separation Altitude (m)	1662	1597 – 1726	1674
Velocity at Backshell Separation (m/s)	77.4	59.2 – 95.3	78.6
Powered Descent Duration (sec)	53.8	50.2-58.1	55.6
Fuel Consumed during Powered Flight (kg)	287.7	279 – 297	270
Constant Velocity Accordian Start Altitude (m)	242	220 – 264	248
Constant Deceleration Start Altitude (m)	142.5	140.6 – 144.5	142.7
Rover Separation Altitude (m)	21.6	20.5 – 22.8	21.5
Velocity at Rover Separation (m/s)	0.75	0.65 – 0.85	0.77
Rover Deployment Duration (sec)	5.4	5.0 – 5.8	5.3
Touchdown Velocity (Descent Stage Vertical) (m/s)	0.75	0.67 – 0.82	0.60
Touchdown Velocity (Descent Stage Horizontal)(m/s)	0.04	0.00 – 0.09	0.12
Landing Miss Distance (Range)(km)	0	0 – 8.11	2.385

Table 1, Flight Predictions vs As-Flown Performance

There were two notable anomalies during the landing night sequence of events. First the x-band radio which was telemetering semaphore tones directly to earth turned itself to stand-

Copyright, 2012 by California Institute of Technology. Published by AIAA, Inc., with permission

by approximately seven seconds prior to the expected loss of signal, due to Earth setting. During landing night this was assumed to be a miss-interpretation of the timing of flight telemetry. Upon closer inspection of the data, it is clear that the radio set itself to stand-by mode, for an as of yet undetermined reason. This is a subject of active investigation.

The second anomaly was the unexpectedly low touchdown velocity. This arose, in the lead author's opinion, from a combination of errors in judgment during the design phase of the mission. Because of issues with the near field stay out regions of the Ka-band Radar, the six-beam antennae lay out was forced to change. During this change, it was decided that only two beams dedicated to operation during the sky crane maneuver would be sufficient. This use of only two beams meant that third direction of the velocity vector would have to be estimated using the IMU and the assumption of a well known local surface gravity. During preflight analysis, a complex 16 mode (check?) model of the local gravity field was used (cite Fred). This was a reduced model of the known 89 mode (?) gravity model that had been constructed by years of orbiter data from Mars Global Surveyer, Mars Oedessy and Mars Reconissence Orbiter (all these contributed?). In fact, there is a notable difference between the two gravity models, due to a mass concentration under the landing site at Gale crater (not surprising considering that some large impact formed the crater).

On landing night, the error in the gravity model that had been used to construct the navigation filter z-axis velocity propagation resulted in an acceleration upward and along the spacecraft x-axis of a magnitude of XX? g's. This resulted in the vertical motion of the descent stage and rover slowing as they approached the surface while simultaneously picking up horizontal velocity (cite Fred). At touchdown, the vertical velocity of 0.6 m/s was well outside any prediction made during the development and analysis process (0.75 m/s +/- 0.1 m/s, 3σ). The lower than planned vertical velocity resulted in reduced touchdown loads on the spacecraft, the increased horizontal velocity, was still within the anticipated range.

The root cause of this anomaly can be traced back to a design error in laying out the beams of the radar. By devoting only two beams to the landing measurement, the system had to rely on a priori knowledge of the environment (in this case local gravity). This reliance on detailed prior knowledge of the environment is antithetical to the design principals used in the formulation of the MSL EDL architecture. This was acknowledge at the time this design choice was made but it was believed that we understood the local gravity well enough to rely on an Earth based model and estimation, rather than direct measurement of the critical quantity of interest, in this case, the third component of the descent stage's ground relative velocity.

There is some poetry in the fate of the landing. That this was really the prime lapse, acknowledged at the time, in the team's design practice and that it would come to pass that the resulting system vulnerability exposed us to risk that was realized during flight, is a great lesson for future expeditions into the unknown of spaceflight engineering. The resulting touchdown velocity error, would have been very likely survivable even if the sense of the error had been reversed (that is higher touchdown velocity of approximately 0.9 m/s). Such a landing, however, would have been survived on the margins carried within the mechanical design of the rover and that was certainly not the design intent.

Copyright, 2012 by California Institute of Technology. Published by AIAA, Inc., with permission

After successful use of this new EDL system and with an appreciation for the inherent margins and estimate of the final flight performance of MSL EDL system should be considered to be the following:

Altitude performance: -1.0 km MOLA or better depending on Ls
Accuracy performance: 14kmx7km ellipse or better (3σ)
Mass delivery performance: 1000 kg or b~~p~~etter depending on Ls

These performance attributes represent a significant improvement in altitude, mass and precision for payload delivery to Mars.

Summary and Conclusion

The MSL entry, descent and landing system represents the latest advancement in the state of the art of payload delivery to the surface of Mars. It is the result of lessons learned across several successful and unsuccessful expeditions to Mars. Although elements of the EDL design, like the sky crane maneuver, may look revolutionary, they should be considered an evolution from the landing systems designs that proceeded. Wise choices in system design allowed successful passage through the development challenges the EDL system faced, and resulted in system performance robust enough to survive those design choices that were not as wise as they should have been. The MSL EDL architecture may have an opportunity to be tested again in 2020 with the surface mission planned for that opportunity. The authors wish those engineers who will carry the design forward into the future all the luck that was had the first time around.

Acknowledgement

The authors would like to thank the members of the entry, descent and landing team from across the country that made this landing system possible, members include staff at NASA LaRC, NASA JSC, NASA ARC, as well as industry and academic partners. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Note to Unlimited Release Reviews:
The formatting, citations and proof reading efforts are incomplete for this work, but the technical content is complete. Spelling and word choice changes and citation additions may occur at a later date, but no content additions will be made.

Copyright, 2012 by California Institute of Technology. Published by AIAA, Inc., with permission