A Matter of Millimeters: Defining the Processes for Critical Clearances on Curiosity

Author: Brandon Florow
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr., M/S 301-490, Pasadena, CA 91109
(818) 354-4210
Brandon.T.Florow@jpl.nasa.gov

Abstract

The Mars Science Laboratory (MSL) mission presents an immense packaging problem in that it takes a rover the size of a car with a sky crane landing system and packs it tightly into a spacecraft. This creates many areas of close and critical clearances. Critical Clearances are defined as hardware-to-hardware or hardware-to-envelope clearances which fall below a pre-established location dependent threshold and pose a risk of hardware to hardware contact during events such as launch, entry, landing, and operations. Close Clearances, on the other hand, are defined as any clearance value that is chosen to be tracked but is larger than the critical clearance threshold for its region. Close clearances may be tracked for various reasons including uncertainty in design, large expected dynamic motion, etc.

Before the Mars Exploration Rovers (MER), critical clearances were tracked by individual cognizant engineers (Cog-Es) or subsystem mechanical leads in an ad hoc manner. During MER a methodology was developed to capture a larger number of close clearances. In 2006, on MSL, the number of close clearances being tracked was expected to grow significantly through the development and implementation phases. In order to deal with the large number of clearances the position of close clearance engineer was introduced and a systematic procedure, implementing and expanding upon the MER methodology, was put in place to define, identify, track, resolve, measure, and disposition clearances. MSL tracked 249 static, 25 separation, and 378 operational clearances.

This paper will define the thresholds for close and critical clearances as well as discuss the differences between static/dynamic, separation, and operational clearances. It will describe the different methods for identifying and flagging clearances; the tools created to track them; the analysis used to understand their risk; and the methods for resolving, measuring, and dispositioning the clearances. This paper will provide an overview of the state of MSL with respect to critical clearances, as well as provide lessons learned for future missions.

Intro

MSL developed a critical clearance policy to handle its large number of close and critical clearances. The primary objective of this policy was to provide a set of guidelines to configure the spacecraft which minimize the risk of unwanted hardware contact caused by flexible body dynamics during loading events, separation dynamics, and operations. This policy also defined the processes for identifying and dispositioning clearances as well as led to the development of tracking tools.

The first step was to define what warranted a clearance being tracked. Thresholds were calculated based on the predicted relative motion between subsystems and were used to identify high risk configurations. Table 1 below shows example thresholds – these are not the values that were used on MSL (note: any item which showed a clearance reduction of >50% of its static clearance was considered a critical clearance regardless of the actual static clearance value).

Table 1: Critical Clearance Thresholds

Static Clearances		**Separation Clearances**	
CS-CS	20mm	CS-EV	25.4mm
CS-EV	30mm	HS-EV	70mm
BPS-BPS	20mm	PDV-BS (after guide rails)	80mm
BPS-DS	10mm	RVR-DS sep envelope	20mm
PDS-DS	30mm	BUD-RVR @ Sep	40mm
BS-DS	50mm	BUD-RVR @ TD	40mm
DS-DS	50.8mm	BUD-RVR @ Release	76.2mm
DS-RVR top deck	40mm		
DS-RVR appendage	60mm		
DS-HS	50mm		
RVR-RVR	20mm		
AS-RVR	40mm		
AS=Aeroshell; BS=Backshell; BPS=Backshell Parachute System; BUD=Bridle Umbilical Device; CS=Cruise Stage; DS=Descent Stage; EV=Entry Vehicle; HS=Heatshield; PDS=Powered Descent Vehicle; RVR=Rover			

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A system to highlight the amount of risk each clearance posed was then developed. This consisted of a numbering system combined with a color coding system to easily identify the highest risks of hardware to hardware contact. With over 650 total clearances being tracked it was important to focus on the highest risks to systematically disposition all clearances. This system is described in Table 2 below.

Table 2: Criticality Numbering

Criticality Number	Definition	Example*
0	Above the criticality threshold	>25.4mm
1	Between 2/3 of the criticality threshold and the criticality threshold	16.9 - 25.4mm
2	Between 1/3 of the criticality threshold and 2/3 of the criticality threshold	8.5 - 16.9mm
3	Between interference and 1/3 of the criticality threshold	0 - 8.5mm
4	Interference	0mm

*Example based on a threshold of 25.4mm

The processes for identifying, tracking, and dispositioning static/dynamic, separation, and operational close clearances are described in the following sections

Static/Dynamic Clearances

Static clearances were focused on early in the design phase. These are clearances between two subsystems that are in close proximity to each other. Static clearances helped to define design envelopes and indentified where subsystem Cog-Es needed more interaction with one another. Dynamic clearances, on the other hand, came into focus a little later in the design phase. Using the list of static clearances being tracked, dynamic clearances added further information that as to the level of risk between hardware in close proximity. While these are two different types of clearances, they were tracked together as they both contribute to the overall risk of a particular clearance.

Process

There were a few different ways of identifying close and critical clearances. First, each Cog-E was responsible for identifying any critical clearance to their hardware and bringing it to the attention of the close clearance engineer as well as the mechanical lead for that system. Second, the close clearance engineer spent hours with the MSL CAD model looking for possible issues. These issues were then brought to the attention of the Cog-Es involved to see what the impact was and decide whether they needed to be tracked. The third way to identify close clearances was to examine the hardware during fabrication/assembly. This method helped to capture any clearances that were missed by the other methods, and caught issues caused by assembly tolerances, hardware not matching the CAD model exactly, and areas not well defined in the model (i.e. prop lines, cabling, blanketing, etc.).

The close clearance engineer was responsible for tracking all of these clearances. A tracking tool was created to easily identify the highest risk clearances and to display a myriad of information. This tracking tool, used for static/dynamic clearances, was an excel spreadsheet with a variety of relevant information to help qualify these clearances. Every clearance was given a 3 digit ID number for easy tracking and was grouped according to the threshold table above (Table 1). Each item included a description to easily identify what hardware was involved. A criticality level was assigned as explained above. The nominal clearance as measured in the CAD model was recorded. Clearance losses due to assembly tolerance, backlash, and launch and entry loads were calculated to get the final clearance value. The actual as-measured clearance (on the flight vehicle) was recorded along with the date of measurement and the procedure number. And the dates that the clearance was first submitted, updated, and closed (along with who approved the closure and why) were also included. This tracking tool was regularly updated and put on a MSL project shared sight and a link was provided next to each clearance to bring up a screenshot of the area in question.

During the tracking phase the close clearance engineer measured (in the CAD model) and reported the top risks to the mechanical leads each week until the clearance was dispositioned. The mechanical leads and the close clearance engineer would work with the Cog-Es to either redesign the affected hardware or analyze it enough to prove that it was an acceptable risk. All critical clearances were presented for PDR and CDR.

During assembly (ATLO) all critical clearances with a criticality of 3, a dynamic clearance loss greater than 50%, or in an area of special interest were measured on the flight vehicle. Measurements were made mostly using tools such as feeler gauges/pins, T-gauges, go/no-go gauges, etc., however, laser metrology was used in areas where there was no physical access. Procedures were generated to verify the measurements. A list was created to track all of the measurements made during ATLO and each measurement was signed off by the close clearance engineer, the mechanical leads for the systems involved, and the ATLO mechanical lead as a part of the close out procedures.

Dynamic Analysis

Dynamic analysis was performed for both launch and entry loads. All clearances with a criticality 3 (unless negligible motion was expected) as well as all clearances with high expected clearance loss regardless of criticality rating were analyzed. The analysis was performed using a finite element model (FEM) with specific clearance items coded in with "feeler gauges" to measure relative displacement.

For each point of interest, a pair of nodes was defined in the spacecraft coordinate frame by the close clearance engineer. These nodes represented the closest approach between two pieces of hardware as modeled in CAD. Rigid body elements (RBE) were used to attach these nodes to their respective components. Relative displacement gauges – basically elements with no mass – were attached to each node to measure the clearance loss. See Figure 1 below as an example (RBE's are shown in yellow and the relative displacement gauge is in red).

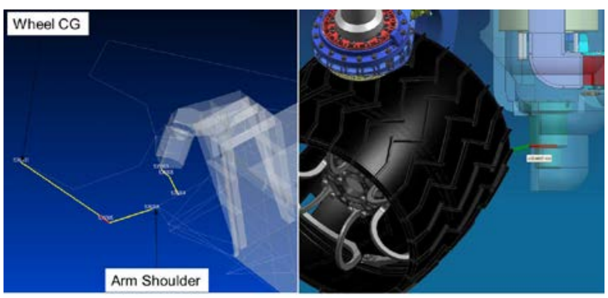

Figure 1: Example of a clearance coded into the FEM (left) compared to the clearance as seen in the CAD model (right)

Separations

Separations in most areas were handled similarly to the static/dynamic clearances. The same tracking tool was used with separation clearances getting an "S" in front of the three digit ID number; and the CAD model was used to identify clearances.

Two areas were found to have issues; CS-EV and DS-RVR. Nominal measurements were made in the CAD model and high risk clearances were measured on the hardware. Clearance losses were calculated differently however. For the CS-EV, in some areas a separation cone was used, creating an envelope around the separating hardware in the CAD model which was analyzed to see if there was an interference. Elsewhere, the CAD model was manipulated, rotating or moving specific hardware to see where there were issues. Both of these methods used maximum values based on the Adams multibody dynamics model. DS-RVR separations were handled differently as that phase presented the most amount of clearances.

Descent Stage to Rover Separation

In September of 2006, preliminary Descent Stage separation envelopes were created in the MSL CAD model to identify DS-RVR clearances. These preliminary envelopes were based on DS-Rover separation dynamics analysis performed using the CAST dynamics model. They included 50% margin, 10mm of design uncertainty, and 25.4mm of clearance. These preliminary DS separation envelopes were attached to the DS CAD model (see Figures 2 and 3).

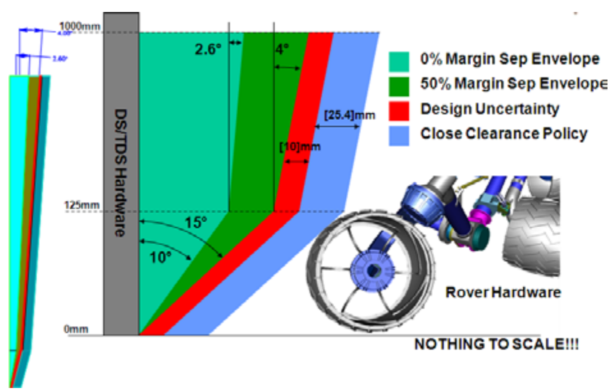

Figure 2: DS Separation Envelope Formulation

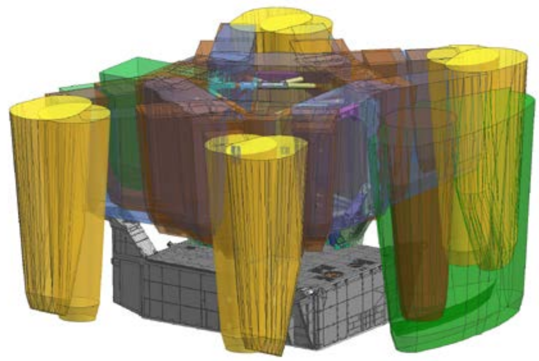

Figure 3: DS Separation Envelopes in CAD Model

Then, the list of DS-RVR separation clearances was generated based on measurements between these envelopes and the Rover CAD model. The separation clearances with the highest criticality (3 or 4) were the focus of a second separations study, which was more accurate and less conservative than the study that led to the creation of the preliminary envelopes. These clearances were examined to provide coordinate points for use in the ADAMS Monte Carlo Separations analysis. These coordinates represented the points in the CAD model that came closest to each other on the descent stage and rover hardware during separation.

In March of 2011, a Monte Carlo Separations analysis was performed to determine the final separations clearance of 27 DS points that were defined using the above method. The 27 points were tracked in the rover frame during the first meter of separation and 1000 simulations were run (see Figure 4).

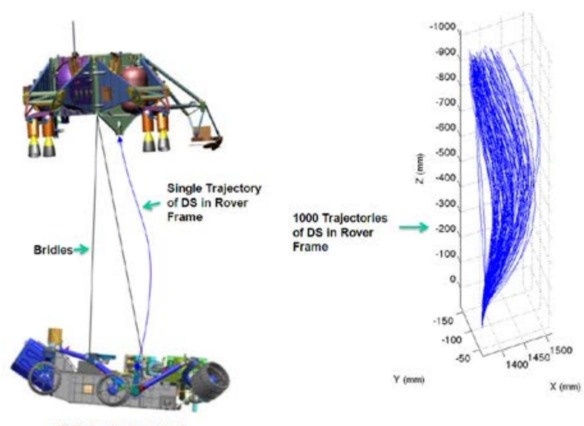

Figure 4: Separation Trajectories

Bounding envelopes were generated using these trajectories. These bounding envelopes were imported into the MSL CAD model (see Figure 5).

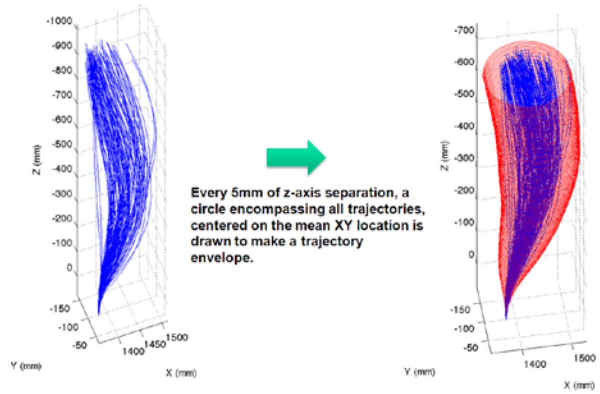

Figure 5: Bounding Envelope

Measurements were then retaken at each of the locations. These measurements were between the new bounding envelopes and the rover hardware. Actual measurements to the separation envelopes could not be done on the actual flight vehicle, as the envelopes are not physical items. However the hardware of interest and their actual close clearances to each other could be measured and compared to the CAD model for verification of hardware positional relationships. These measurements were made using the same process as defined in the static/dynamic clearance section above.

Any separation clearance less than 25mm was reviewed by the MSL EDL Systems Team and Mechanical Engineering teams and has been approved as acceptable. Although in violation of the Close Clearance Policy, these items, either by design could not meet the minimum 25mm clearance or were reviewed and approved as a non-snag or not a separation hazard.

Operations

Operational close clearances were by far the most abundant. This was simply because there were several configurations that needed to be checked with several variables in each configuration. They required a separate tracking tool with different information and were disposition in a different way.

Process

Identifying operational clearances started with identifying all of the configurations that the rover would be in during surface operations (and all of the variables for each configuration). This was a list of all of the possible tool placements (Portioner dropoff to CHEMIN, Drill to Bit Box, DRT to Observation Tray, etc.). This included both a nominal position as well as a teach point (a predefined location above or in front of the target that the arm would go to before moving to the nominal position for operations) – as well as some off nominal positions for certain configurations. On top of these different configurations there were also envelopes to consider. These envelopes (Scoop, Inlet Covers, Mobility, etc.) were swept volumes of actuated hardware on the Rover used to check if there were problems when the hardware was open, closed, or in an unknown state.

The arm was then placed into these various configurations in the CAD model and close clearances were recorded. The same criticality rating system was used to identify the clearances with the highest risk, but the tracking tool was slightly different. A three digit id number was still assigned to each clearance. Other similarities were the description, nominal clearance, measured clearance (with procedure number), and dates. What changed was how the clearances were grouped and the fact that clearance losses were no longer calculated. Because there were several variables used in defining the configurations, the clearances were grouped based on the tool involved (Portioner, Scoop, Drill, etc.), the receiver (SAM, Poker, Calibration Target, etc.), the position (how far above or in front of the receiver the tool was), the location (nominal, port side, etc.), and whether or not an envelope was being checked.

During testing both on the flight vehicle and on the engineering model, several measurements were made to compare the clearances identified in the CAD model with actual hardware. Because not every configuration was tested, not every clearance was measured. However, the amount and variety of clearances that were measured proved that there was a strong correlation between the CAD model and the actual hardware and therefore the nominal clearances in the CAD model were sufficient.

Clearances were reviewed with the close clearance engineer and the SA-SPaH (Sample Acquisition – Sample Processing and Handling) mechanical lead. They were dispositioned as one of the following:

A - Use As Is – the clearance doesn't pose a risk of hardware damage.

B - Fault Case (Update Operational Rules) – this was used for envelope clearances. If the scoop, inlet cover, etc. failed these clearances would need to be revisited based on the type of failure (open, closed, or unknown). The clearances identify configurations where there would be a problem and the operational rules would need to be updated to reflect that.

C - Write Flight Rule – this was used for known, persistent issues such as the mobility interfering with the arm in certain configurations or the Portioner only being able to reach certain points on the Engineering Tray. Flight rules would need to be written to restrict motion in these areas.

D - Hardware Redesign – used to identify areas that needed work (no clearance was closed with this disposition)

E - Obsolete – hardware was redesigned or configuration was no longer necessary making this clearance a nonissue.

Collision Avoidance Model

For operations, a collision avoidance model was created to ensure that no hardware would collide during Rover movements. This model was created using envelopes that encased Rover hardware. The model would check to make sure that the envelopes never touched when the Rover was commanded to move. This ensures that there is margin during operations and no hardware is damaged from inadvertent contact.

The collision avoidance model was tested using the Rover engineering model. The turret was positioned in a series of configurations that brought it into close proximity with rover hardware and the tolerance on the collision avoidance model was increased until a collision was detected. The actual clearance of the hardware was then measured and compared to the model. The results showed that the collision avoidance model detection was comparable with the as measured clearances and was conservative, ensuring no damage to the hardware.

Lessons Learned

Future missions will benefit from the processes created during MER and expanded upon during MSL for dealing with close clearances. Using the process described in this paper and tailoring it to the mission's specific needs will ensure that this is an area of minimal issues.

Defining the clearance thresholds early in the design phase will save time and money in the future. Creating a critical clearance policy fairly early on in the design phase helped MSL to catch problems early. This gave engineers plenty of time to analyze and fix these issues with minimal impact to cost and schedule.

Large projects (as with MSL) should consider a close clearance engineer as the main focus for clearance issues. Without a single point of contact issues can be lost, or not discovered until too late.

Maintaining regular communication is very important. Weekly meetings made sure that everyone involved (close clearance engineer, mechanical leads, Cog-Es, designers, etc.) were on the same page and were aware of any and all issues with the design.

CAD systems are not always good modelers of certain subsystems such as propulsion lines and especially cabling. These systems should be looked at early, often, and thoroughly. And margin should be held for any CAD measurements. Cable mockups for MSL helped to identify issues not seen in the CAD model, and examining the hardware as soon as it was available caught issues as well. Also, items such as MLI are often not modeled and should be considered when trying to identify problem areas.

Many areas are hard to access during ATLO for verifying clearance measurements. Having a clear plan as to which methods will be used for which clearances as well as when measurements will be made in the ATLO flow is important. Without such a plan clearances that need to be verified can be missed. The close clearance engineer on MSL worked with the Cog-Es, mechanical leads, and ATLO lead to identify when hardware would be accessible and what method could be used to ensure that all measurements were made. (A special thanks to the technicians who, at times, had to become contortionists to get to some of these measurements).

Conclusion

MSL was launched in November 2011 and landed on August 5th, 2012. Even though it is one of the biggest and most complex systems JPL has ever built and was packed tightly into an Entry Vehicle with a Skycrane there have been no issues from hardware to hardware contact. This mission continues to operate on the surface of Mars without clearance issues.

The clearance policy of MSL was very successful. The process defined in this paper identified, tracked, analyzed, measured, and dispostioned over 650 items. There were 274 static/dynamic and separation clearances, with 128 measurements made on the flight vehicle. 378 operational clearances were also identified with 68 measurements made on the flight vehicle and engineering model; and more measurements were made during the collision avoidance model testing as well. Detailed studies were conducted, trades were made, and hardware was redesigned in some cases. Dynamic analysis verified that no interferences occurred during launch or entry. The final separations study showed that no interferences were indicated for any of the areas of biggest risk for contact during separation. The disposition of the operational clearances along with the collision avoidance model ensures that no interferences will occur during surface operations.

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