Mechanical Accommodation of Mars Science Laboratory Surface Thermal Requirements
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Abstract—The Chassis structure of the Mars Science Laboratory Rover is designed to be exposed to wide-ranging temperatures throughout all phases of the mission. The most extreme of these conditions occur once the rover has arrived on the Martian surface. The external, uncontrolled, structure is expected to experience a range of temperatures from minus-130ºC to 40ºC. Payload and housekeeping equipment are mounted on an internal, thermally-controlled panel. The temperature of the internal panel is controlled to range between minus-20ºC and 50ºC.

This paper describes the novel method used for supporting the thermally controlled panel on the uncontrolled structure. The method described allows for large magnitude thermally induced relative motion between the panels while it simultaneously provides a controlled thermal resistivity between the two panels. The resulting design is also capable of withstanding the accelerations of atmospheric entry and provides sufficient stiffness to ensure its motion is significantly de-coupled from that of the launch vehicle.

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1. INTRODUCTION
The Mars Science Laboratory (MSL) Rover is a mobile platform designed to collect samples of rock, dust, and atmosphere from the surface of Mars and analyze it for evidence of past or present life. It is an extremely complicated system of instrument and housekeeping subsystems all designed to operate over specific temperature ranges.

In order to provide the most flexibility to the science team supporting the mission, the Rover is designed to land across a wide swath of the planet, from 45° north to 45° south latitude. A requirement to operate across such widely varying environments is the ability to handle extreme temperature variations. The Chassis structure is designed to provide a thermally controlled plate for mounting avionics that is substantially isolated from the rest of the uncontrolled structure.

A thermal control system has been devised to transport heat around the Rover via a liquid cooling loop. This loop is used to transport waste heat from the Radioisotope Thermal Generator (RTG) to the equipment when needed and to transport dissipated heat from the electronics out to radiator surfaces.

Figure 1 - Rover Chassis Structure
The Rover Chassis is an aluminum box structure (Figure 1). Five sides of the structure are comprised of machined aluminum panels and beams. The structure is closed out by an aluminum face sheet / aluminum honeycomb sandwich panel. The external structure is allowed to vary in temperature with the environment. It is referred to as “cold” structure. Internal to the Chassis is another aluminum plate, used to support the Rover Avionics and Instruments. This plate is referred to as the Rover Avionics Mounting Panel (RAMP). This plate is thermally controlled, “warm”, structure. It is the support of the RAMP to the “cold” structure and the accommodation of the liquid cooling loop that is the topic of this paper.
2. DESIGN REQUIREMENTS

The design of the interface between the RAMP and the Rover Chassis is influenced by thermal as well as structural design requirements. Thermal and structural requirements are often at odds with one another. Balancing these requirements has been the greatest challenge of this design.

To ensure mission success the RAMP / Top Deck Interface must be designed to:

* provide mounting interfaces for the Rover Avionics and Instrument components;
* fit within the Rover Chassis size constraints;
* accommodate Heat Rejection System (HRS) tubing;
* carry the loads induced through the launch/entry and touchdown/traverse environments;
* be stiff enough such that the fundamental mode of the Rover Chassis is above 18 Hz;
* have compliance to allow significant differential thermal expansion at extreme temperature conditions, and
* meet a minimum thermal isolation requirement.

Each of these requirements will be addressed in turn.

Mounting Interfaces

The MSL Rover Chassis is home to seven Science Instrument components, eight Avionics and housekeeping components, and numerous Telecom and Command & Data Handling components. Refer to Figure 2 for the internal configuration of the Chassis.

Size Constraints

The Rover Chassis is constrained in overall height. The height of the chassis is driven by landing clearance requirements and by the height of the largest components mounted inside. A small gap between the internal components (including harness) and the bottom panel of the chassis is required to provide sufficient insulation in the rarefied CO2 of the Martian atmosphere.

HRS System Interfaces

Both the RAMP and the Top Deck are required to support interfaces with the Heat Rejection System. The tubing on the Top Deck is part of the larger radiator system and is used to control the temperature of the working fluid. The
tubing on the RAMP is used to transport heat to and from the specific components mounted to the RAMP. With the large number of components mounted to the panel, this requirement heavily drives the implementation.

Driving Load Cases

The Rover Chassis is designed around two distinct restraint conditions, launch / cruise / entry / descent, and touchdown / traverse. In the launch/cruise/entry/descent condition, the stowed Rover is secured to the Descent Stage in what is known as the Powered Descent Vehicle (PDV). The loads of the entire rover are carried through three shear cone interfaces to the supporting structure. During launch, cruise, and entry, the PDV is secured to the Backshell Interface Plate (BIP) which also supports the entry Aeroshell. This combination is referred to as the Entry Vehicle (EV). During launch and cruise, the Entry Vehicle is secured to the Cruise Stage [1].

Upon arrival of the Cruise Stage to Mars, the Entry Vehicle separates from the Cruise Stage and begins atmospheric entry. Once safely into the atmosphere, the supersonic parachute deploys, slowing the EV down. Following parachute deployment, the heatshield is jettisoned from the EV. Once the EV has reached the appropriate altitude, the PDV separates from the Backshell and begins a controlled descent toward the surface of the planet [1].

Once the PDV reaches a specific low altitude, the Rover is separated from the Descent Stage and lowered to the ground via three bridles played out from a rate limiting device. This configuration is known as the Sky Crane [1]. During the descent of the Rover from the Descent Stage, the Mobility system is deployed. Upon touchdown, this system absorbs and reacts the loads from the rest of the Rover.

Like the Chassis as a whole, the RAMP / Top Deck Interface design is driven by differing load cases. The design of the structure of the machined RAMP panel is driven by the Random Vibration environment at launch as computed using a Modal Mass Acceleration Curve (MMAC) analysis. The Top Deck is driven in different areas by launch (via the MMAC), touchdown, and entry. The connection between the RAMP and the Top Deck is driven by the entry load case in the vertical (normal to the panel surface) direction and the launch MMAC case in the lateral direction.

The maximum vertical load on the Rover occurs as the entire Entry Vehicle decelerates upon entry to the Martian atmosphere. The rover experiences a deceleration of 15g’s which tends to pull the RAMP and all of its components away from the remainder of the rover chassis.

Stiffness

In order to meet requirements on the controlled descent of the PDV, the Rover must have a fundamental frequency of greater than 18 Hz. The first few modes of the Rover are caused by the motion of the stowed mobility system. The first mode of the Chassis structure occurs a few Hertz higher and is a drum mode of the Chassis Top Deck (Figure 3.)

Thermal Compliance

During surface operations, the temperature of the Rover Chassis can range from -130°C to +30°C while the temperature of the RAMP is controlled to between -20°C and 50°C. The worst case temperature differential occurs during the coldest case and is 110°C. Over a large (nearly 1.5 m long) aluminum panel, this temperature differential causes significant amounts of displacement.

While not an optical bench, the RAMP still must meet flatness and alignment requirements for mounting the avionics and scientific instruments. The design must allow for thermally induced motion while minimizing the induced loads.

Thermal Isolation

The thermal control of the Rover Chassis is a combination of active and passive heat management. The aforementioned Heat Rejection System (HRS) actively moves heat around the chassis to where it is most needed or to where it can be radiated away. Insulation and isolation is used to manage the transfer of heat to maintain the control authority of the HRS and to protect the working fluid in the HRS from freezing under extreme conditions.

The RAMP / Top Deck interface is designed by both the desired thermal conductance and insulation between the RAMP and Top Deck. If the area of the facing surfaces is minimized, they can be as close as 6mm and still provide an acceptable and predictable amount of insulation.
3. RAMP TO TOP DECK INTERFACE

The RAMP is mounted to the Top Deck with a series of Titanium flexures. Four of these flexures are designed to take loads in one lateral direction and the vertical direction. These flexures are referred to as blade flexures. The remaining flexures are designed only to take vertical loads. These flexures are known as post flexures.

The four blade flexures are arranged around the perimeter of the RAMP, roughly along the centerline of the panel edges. The post flexures are located strategically around the interior of the panel. Figure 4 shows the arrangement of the post and blade flexures on the Top Deck without the RAMP in place.

Finite element analysis shows that this arrangement of blade and post flexures is the most effective in supporting the RAMP through the various load cases described above. The four blade flexures, arranged in pairs carry the lateral loads on the RAMP during launch. The flexures are oriented such that their compliant direction is along the lines of thermal growth. They allow the RAMP to grow relative to the Top Deck but still carry the forces and moments from lateral loads.

The number and location of post flexures is determined by finite element analysis of the structure of the RAMP and Top Deck. The arrangement allows for the satisfaction of both the load case and stiffness requirements. The RAMP and Top Deck are both irregularly ribbed machined panels. The location and orientation of the ribs was driven by both the location of components on the RAMP and Top Deck and the need for a strong load path for primary structural loads in the Top Deck.

The Top Deck serves as an integral piece of the primary structure. It carries the shear loads from the three descent stage cup/cone interface locations. It forms the backbone on which the touchdown loads from the mobility system are reacted. It supports several pieces of high mass equipment, and it carries the load of the entire Rover during the “sky crane” operation as the Rover is lowered to the Martian surface. With these load cases in mind, a fundamental primary backbone rib arrangement was developed. A secondary arrangement of ribs was driven by those required by the RAMP.
The rib structure on the RAMP is driven by the location and arrangement of the components it supports. It is desired that the components, especially those of heavy mass, be fully supported along their bolting interfaces by ribs that run across the full length and width of the panel. In certain locations, it is not possible to completely span the entire panel and the ribs are terminated at locations near supporting post flexures.

The rib structure of the RAMP and Top Deck are essentially mirrors of one another. With the layout known, the post flexures are located at key intersections of ribs on both panels.

The purpose of the post flexures (Figure 6) is to carry the axial loads between the panels to provide out-of-plane stiffness to the RAMP, to control relative motion between the RAMP and Top Deck, and to be compliant in lateral directions to allow the RAMP freedom to grow thermally relative to the Top Deck.

The post flexures are made from titanium and are designed to carry tension and compression loads. The moment carrying capability at the ends of the post is relieved by orthogonally aligned blades. The blades are oriented at each end such that the effective length of the flexure is the same for each set of blades. This arrangement gives the post identical performance in any lateral direction. As a result of this feature, the flexures can be installed independent of orientation.

The opposed blades at each end of the post flexure are separated by a wedge rather than located directly upon one another. This wedge allows the load from one blade to be spread out and fully carried by the opposed blade below it. Insufficient spacing between the blades causes a load concentration at the point where the blades meet and can be a cause for failure.

The post flexures are designed to be as long as possible given the overall height constraint. Longer flexures provide more flexibility for a given strength and also provide more thermal isolation than shorter flexures.

The blade flexures (Figure 7) are also made from titanium and are designed by shear loads and compressive buckling. They are designed to allow translation in one direction and for moment release at each end.

The blade flexures are aligned to the Top Deck and RAMP during assembly and are match drilled and pinned to both panels. They are pinned along their centerline and bolted in four locations. A Teflon impregnated anodic coating is used on the mounting surfaces to provide for controlled slip at the four bolting interfaces to accommodate the coefficient of thermal expansion mismatch between titanium and aluminum.

Recall that in addition to the structural requirements on the design, there are also strict thermal conductivity requirements. The blade and post flexures are both made from titanium, and they are designed to allow for maximum lateral compliance in at least one direction. These characteristics allow for them to provide relatively low thermal conductivity between the RAMP and Top Deck. The arrangement as shown here provides a specific thermal isolation between the RAMP and Top Deck. No additional isolation is required to satisfy the thermal conductivity requirement.
4. HRS SYSTEM ACCOMMODATION

The most challenging aspect of the RAMP / Top Deck Assembly is the integration of the Heat Rejection System (HRS) tubing. Integrating the tubing into the design involves closing the gaps in the structure required to provide a path for the tubing and providing high thermal conductivity channels in which to install the tubing. On the RAMP alone, over 12 meters of tubing are installed.

Installing this tubing involved cutting structural ribs on each panel. On the Top Deck, as part of the primary structure, keep out zones were established for the primary load paths. These ribs are not to be cut, since no suitably capable closure technique is available to handle the high loads. On the RAMP, structural loads are lower, and thermal considerations are dominant. Nearly every structural rib on the RAMP is cut to provide access for tubing.

For the Top Deck, an additional requirement is that the tubing be located on the aft half of the structure. The forward section of the Chassis gets too cold to ensure that the working fluid would not freeze and adversely impact the HRS.

Two types of closure brackets are required on the panels; plate closures and tee closures. Plate closures are used in locations where there is sufficient access across the tube cutout to allow shear fasteners to be installed on either side of the cutout. Tee closures are used where the tube path passes too close to an existing rib and shear closeouts are not possible.

The plate closures are designed to transfer the shear and compressive / tensile loading across the tube opening in a couple with the panel skin. A large radius is placed at the base of the rib near the cutout to allow the loads to transfer into the skin over a larger area. This arrangement prevents the load from concentrating at a point where the rib and skin meet. The shear loads are carried directly through the shear capable fasteners used to secure the bracket to the panel. These fasteners are also capable of transferring the loads due to the bending moments being carried through the rib.

The tee closures are designed to transfer the same loads as the plates, but convert the loads into tension / compression at the base of the tee. Close tolerance fasteners are used to ensure that shear loads are carried.

To provide high thermal conductivity from the mounted components to the tubing, the tubing is routed in channels at key locations on the panel. These channels are machined directly into the panel and are designed to allow for tubing manufacturing tolerances and to allow a good conductive path into the whole of the tube circumference. To accomplish this goal, the tube is bonded onto the panel and is potted into the channels with a thermally conductive epoxy. The heat path is closed around the tube in the channel locations with a cap that is co-bonded with the tubing. The tubing channel and the cap mounting interfaces are machined with high precision due to the sensitivity of the heat path to the thickness of the bond line. Figure 10 shows the cap installation and is illustrative of the complexity of the tube path on the RAMP.
5. CONCLUSIONS

The thermal environment on the surface of Mars is a significant driver in the design of the MSL Rover Chassis. The mechanical accommodation of the thermal control system required for the operation of the Rover on Mars is discussed in this paper. The discussion centers on the interface between the thermally controlled Rover Avionics Mounting Panel and the uncontrolled Chassis Top Deck.

The Rover Avionics Mounting Panel is required to be kept at an operating temperature between -20 C and 50 C. The Chassis structure can reach temperatures as cold as -130 C. For a large aluminum structure, temperature variations of 110 C cause significant thermal distortions. The design of the interface from the Rover Avionics Mounting Panel to the Chassis accommodates these large displacements.

The Rover Avionics Mounting Panel is supported on the Top Deck by means of a series of titanium flexures. These flexures are designed to carry the load of the fully populated panel throughout the launch, entry, and landing load cases while allowing for the thermal expansion of the RAMP relative to the Top Deck.

In addition to the thermally induced loads, the RAMP structure is a key component of the overall thermal architecture. The panel must accommodate over 12 m of tubing carrying liquid coolant. The interface of the RAMP to the Chassis structure must have a low thermal conductivity.

The design presented in this paper meets all of the above requirements in a robust way. However, improvements can always be made. Integration of the tubes to the panels is a time consuming operation involving match drilling. Over 130 structural closures are installed on the structure. These closures also imposed a significant mass penalty to the design. Future designs for this type of structure should consider other options for tube integration that may be more time- and mass efficient.

REFERENCES


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BIography

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