MICRO-IMAGER DUST COVER, MICRO-IMAGER CONTACT SENSOR, AND MÖSSBAUER SPECTROMETER CONTACT SENSOR MECHANISMS FOR THE MARS EXPLORATION ROVERS

Sean Dougherty

Alliance Spacesystems, Inc.
1250 Lincoln Ave. Suite 100
Pasadena, CA 91103, USA
http://www.asi-space.com
(+001)626.296.1373 x133
(+001)626.296.0048 fax

Abstract

This paper discusses three mechanisms developed for the Mars Exploration Rover (MER) program which will land two rovers on the Martian surface in January 2004: the Microscopic-Imager Dust Cover, the Microscopic-Imager Contact Sensor and the Mössbauer Spectrometer Contact Sensor. These mechanisms enhance the capabilities of the rovers and their in situ science instruments, specifically the Microscopic-Imager (MI) and Mössbauer Spectrometer (MB), located on the end of the rover's robotic arm. The MI Dust Cover mechanism covers the lens of the Microscopic-Imager protecting it from dust and incidental contact while the instrument is not in use. The cover opens when the MI is positioned over a target and closes after a series of images has been taken. The MI and MB contact sensors, as their name implies, sense contact with the Martian surface, indicating that the instrument is positioned at the proper distance from the target and can begin taking measurements.

While the functions these mechanisms perform are fundamentally simple, the implementation of the mechanisms under typical constraints (mass, schedule, budget, science requirements, etc…) provides an excellent illustration of the subtleties involved in designing a mechanism for use on Mars, interfacing to existing hardware, and working to conflicting requirements. Very few mechanisms have been designed to sense contact with an extraterrestrial surface (or to protect an instrument from the Martian environment), and fewer yet have successfully touched the surface of Mars. As we continue to expand our reach beyond Earth, these mechanisms will become more prevalent and increasingly important. For this reason, a discussion of how these mechanisms are implemented, what issues are important to the scientists, what the relevant trades and requirements are, and what work has been done before (and lessons learned from that work) is essential. This paper presents, in detail, precisely those topics.

Introduction and Background

MER Mission and Science Objectives

The Mars Exploration Rover (MER) program began to take shape in the summer of 2000 with the goal of landing two rovers on Mars in January of 2004. MER (illustrated in Figure 1) is part of NASA's continuing effort to explore Mars and, like previous Mars missions, primary responsibility for its development was given to the Jet Propulsion Laboratory (JPL).

Figure 1. MER on the surface of Mars [1]

The decision was made to launch two rovers to reduce risk and increase science return. Instead of a lander with a separate, small rover like the Mars Pathfinder mission, the entire MER lander is, itself, a rover. The rovers are much bigger than the Sojourner rover of the Pathfinder mission and can rove much greater distances (up to 100m each day). The science package for MER is known as the Athena payload. The Athena payload consists of six primary instruments [2]. Two of these, the Pancam camera and the Mini-TES spectrometer are mounted to the body of the rover. The other four instruments are located on the end of a robotic arm referred to as the Instrument Deployment Device, or IDD (Figure 2).

The IDD along with the associated electronics and software algorithms required to position each instrument at its target constitutes the complete Instrument Positioning System (IPS). The four instruments residing on the end of the IDD are: the Microscopic Imager (MI), the

Mössbauer Spectrometer (MB), the Alpha-Particle-X-Ray Spectrometer (APXS), and the Rock Abrasion Tool (RAT).

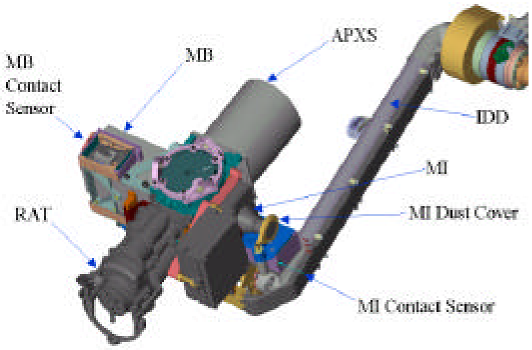

Figure 2. IDD with associated instruments

Because portions of the Athena payload had been proposed before, many of the Athena instruments existed before the detailed design of the MER mission had even begun.

Contact Sensor and Dust Cover Mechanisms

Although most of the Athena instruments had already been developed, they required some enhancements to accomplish MER specific objectives. These enhancements were the addition of contact sensors to the MB and MI and a dust cover for the MI. ASI was contracted to design and deliver the contact sensors and dust cover as part of ASI's contract to JPL for the IDD subsystem. The two contact sensors and the dust cover (often referred to as the instrument mechanisms from here forward) are illustrated in Figure 3. This paper outlines the design of these three mechanisms and the subsequent lessons learned.

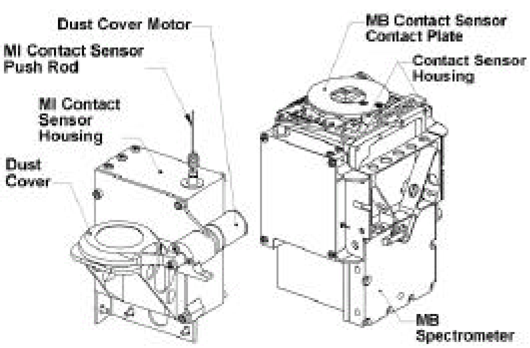

Figure 3. Contact Sensors and Dust Cover

Requirements

JPL and MER Project Requirements

Because of the scope and importance of this mission, and perhaps because of past mission difficulties, the project was classified as a "class B" mission. This is essentially the highest level of quality control and mission assurance a project can have at JPL. This had many effects on the project and the design of the instrument mechanisms. Whenever possible, the lowest-risk design approaches were used and all designs had conservative factors of safety backed up by analysis and testing. Using flight heritage components was essential and R&D efforts were discouraged (because of both the risk and the time involved).

Designing for Mars

The three mechanisms discussed in this paper are fundamentally simple but they provide an interesting illustration of how even seemingly simple mechanisms require a large design effort and careful attention to detail when they are one-of-a-kind designs that will be used on the surface of Mars. The Martian environment places many demanding requirements on the design. Some of these are common to earth orbiting missions while others are unique to Mars. Some of the requirements include [3,4]:

- *Temperature:*
  - –70°C (-55°C for dust cover) to +45°C operational
  - –120°C to +110°C survival
- *Pressure:*
  - 10^{-14} Torr vacuum during cruise
  - 5-10 Torr Martian atmosphere
- *Mars surface:* Fine dust; high winds
- *Radiation*: Up to 15krad TID
- *Life*: 90 cycles (one per day)
- *Humidity:* 30% to 70% RH
- *Launch & Landing Loads*:
  - 42g's from landing impact
  - 60g's launch (from MAC)
- *Others*:
  - Operate in a 1g environment
  - Fit within very small volume
  - Motor torque margin of 2.0

IPS Requirements

The IPS is required to position each instrument on a target to within ±5mm and 10 degrees of the desired position [4]. To accomplish this, and to protect the IDD and its instruments, each instrument requires a contact sensor. The RAT and APXS had already incorporated contact sensors in their design, but the MI and MB needed to have them added.

The robotic arm is capable of approaching a target from almost any angle, and in doing so there may be components of motion that are not perfectly normal to the target. This necessitates a contact sensor design capable of withstanding side loads as well as normal/axial loads. In addition, the contact sensors must be capable of a relatively long stroke (≈3mm) to allow the arm to stop at the correct position without over loading the arm, causing potential damage or causing it to be in the wrong position.

Science and Instrument Requirements

One of the challenges in designing the instrument mechanisms was that the instruments with which they had to interface already existed. In addition, in some cases, there were slight variations in the design of the instrument engineering models and each of the flight models. This necessitated a contact sensor design that was flexible enough to mount to instruments with these slight variations.

Another consideration affecting the design was that the MB has a radiation source, which must be installed immediately prior to launch. The MB contact sensor must be easily uninstalled and then reinstalled without time consuming adjustments or calibration.

Operationally, the contact sensors must be able to sense contact on hard rock, soft soil, and uneven surfaces. They must be able to fit within the hole made by the RAT and they must not block the field of view of any of the instruments. They must actuate with very little force so that the sample is disturbed or compressed as little as possible. And, they must provide feedback protecting the instruments. The MI has the additional requirement that its lens be protected from dust when it is not being used. The dust cover provides this function while, at the same time, avoiding any failure modes that would prevent the MI from gathering data.

Design

Microscopic Imager Contact Sensor

The final design for the MI contact sensor is illustrated in Figure 4.

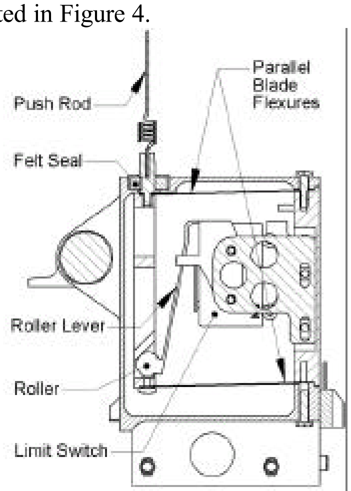

Figure 4. MI Contact Sensor

At the heart of the mechanism lie two Honeywell® limit switches. The limit switches utilize a lever to reduce the force necessary to actuate the limit switch and a roller to avoid sliding contact (increasing reliability). Actuation of the limit switches is accomplished via a 45° ramp, which allows the limit switches to be placed on their side preventing any damage to them (in the event of over-stroke). Parallel blade flexures at the top and bottom of the mechanism provide the necessary motion along the axis of travel while preventing motion in any other direction. The push rod serves as the actual interface to the target. Its length was chosen to indicate contact at the proper distance from the target. Coils integral to the push rod form a spring allowing it to deflect under side-loading conditions instead of bending or breaking. Under normal operating conditions, the push rod will not deflect. However, if deflected, the push rod will still provide the necessary force to actuate the limit switches. The entire mechanism is contained within a thin-walled aluminum housing with a felt dust seal providing protection from the environment.

Mössbauer Contact Sensor

The MB contact sensor, shown in Figure 5, is fundamentally similar to the MI contact sensor.

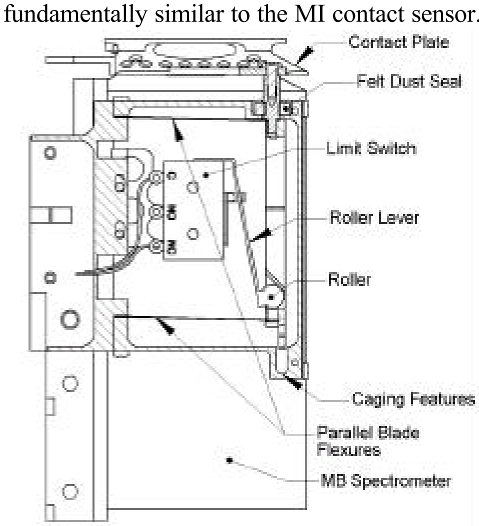

Figure 5. MB Contact Sensor

The limit switch configuration and parallel blade flexure design remain the same and the housing with felt dust seal is also similar. The MB contact sensor, like the MI contact sensor, utilizes two limit switches. However, the two limit switches are in two separate housings, one on each side of the instrument. The other major difference is that the interface to the target is a contact plate. This contact plate provides more surface area so that contact with soft soil can be accomplished with little force.

Dust Cover

The MI Dust Cover (Figure 6) is part of the same assembly as the MI Contact Sensor.

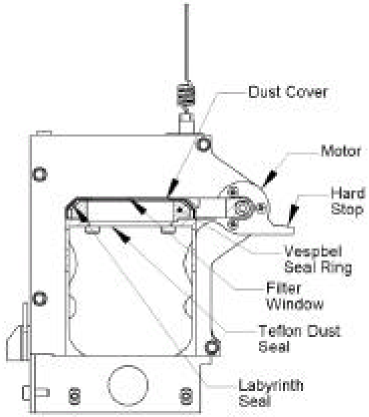

Figure 6. MI Dust Cover

It is a simple, single hinge, cover attached directly to the shaft of a motor. The motor is an Aeroflex®, 10mm stepper run open-loop. There is no feedback, other than camera images, to indicate that the cover is fully open or closed. It is simply run for a set number of steps until it reaches a hardstop. The cover is a window material sandwiched and bonded between two pieces of aluminum. This window allows science data to be collected even in the event of a motor failure. It also provides the added benefit of a filter and a calibration tool to augment the science. To keep dust out, the cover has a simple labyrinth on the top (movable) side and a Teflon seal on the under (non-moving) side.

Initial Research and Decisions

There are myriad ways to sense contact with or proximity to an object. Some sensors require physical contact with the surface being measured while others are non-contacting. Non-contacting sensors include vision systems, infrared and other photo diode systems, acoustic (ultrasonic) proximity sensors, laser range finders, radar devices, capacitive sensors, inductive sensors, and magnetic sensors. Devices that require contact with the surface include limit switches, pressure transducers, strain gauges, piezoelectric sensors, various whiskers (fiber optic, conductive, shape memory alloy etc.) and motors (current monitoring). With so many options for sensing contact with an object, it was challenging to determine which was the most appropriate solution and which would be the most reliable. After researching what had been flown before, what sensors were used in industrial robotics, consulting with people that have solved similar problems, and meeting with JPL to iron out requirements, the focus was directed toward using limit switches as the sensor [5,6]. Limit switches are very reliable (when implemented properly) and have heritage on many spacecraft (including Mars Pathfinder) making them a good choice for this application.

In addition to using a heritage sensor, both the MI and MB contact sensors use two limit switches to provide redundancy. Another decision that was made early on was to combine the MI contact sensor and dust cover into a single unit. This was done to reduce mass and volume as well as to simplify the integration to the instrument.

For the dust cover, several different designs were considered including: a sliding door, multi-hinged doors, and iris diaphragm mechanisms. Due to its simplicity, however, a cover with a single hinge soon became the obvious choice. A 10mm stepper motor was chosen to drive the cover open and closed because it had already been qualified for another application on the rover and provided sufficient force to keep the cover in position even while unpowered.

Preliminary Designs

With the basic elements of the contact sensor and dust cover selected, the focus turned to designing the rest of the mechanism. For the contact sensors, the problem boiled down to a mechanism that would have sufficient stroke, actuate with very little force at any angle from which the target could be approached, and be robust enough to withstand side loads.

Initial concepts focused on a mechanism that was free to move in multiple degrees of freedom but only actuated with motion along the desired axis of motion. Other designs examined constraining all degrees of freedom except for the single degree of freedom required for actuation. These "pure" designs, while consummate from a kinematic standpoint, were too big or too complicated for this application. Other concepts sacrificed little in terms of the ideal kinematics while providing a simpler, smaller, more reliable system. One such system, illustrated in Figure 7, had a simple plunger that actuated the limit switch and a spring to return the plunger when removed from the target. To accommodate side loading there are essentially two options: make things strong enough to take the side loads or make them flexible enough to bend out of the way (or both).

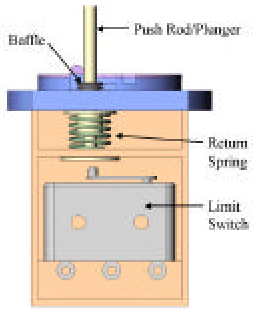

Figure 7. Preliminary concept

Methods for housing the mechanism to protect it from the Martian dust were also considered. These housings varied from simple film or tape enclosures to metal boxes surrounding the entire mechanism. In the end, an aluminum enclosure was chosen because it offered complete protection from dust and debris with a mass that was only a couple of grams more than the lightest options considered. The housing required a dust seal between itself and the moving parts of the mechanism. The preliminary design for this seal was a baffle (also shown in Figure 7).

Initial designs focused on contact sensors that would work equally well on rock and soil, but after several iterations, it was decided that the contact sensors would provide greater flexibility if one was optimized for soil while the other was optimized for rock (although both will work to various degrees on many different surfaces). The two different designs are illustrated in Figure 8.

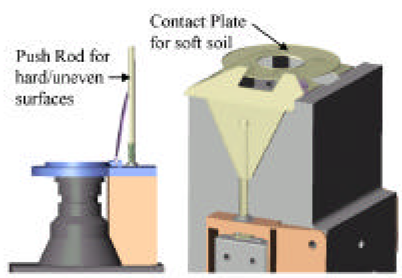

Figure 8. Designs optimized for rock & soil

The MB contact sensor is optimized for soil. It has a large plate to provide surface area and actuates with very little force. It will actuate against a hard surface equally well but, if that surface is irregularly shaped, the exact distance to the target will not be precisely known. The MI contact sensor is capable of more precise positioning on hard, irregularly shaped objects but will be much less effective in soil.

The next focus was how to provide the best seal against dust, while still being easy to integrate to the instrument. A labyrinth seal was incorporated into the cover as shown in Figure 9.

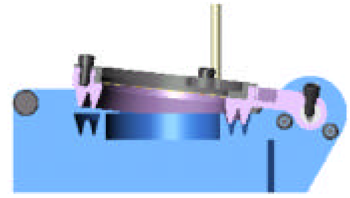

Figure 9. Dust Cover partially open

Refining the Design

The initial designs, though elegant in their simplicity, had some inherent problems. The sliding motion of the plunger designs was a drawback because it could easily jam in a dusty environment, especially with the low forces it was intended to actuate under. Also, even though they are simple in concept, limit switches have several idiosyncrasies that had to be taken into account. The original orientation of the limit switches made them prone to damage. The challenge now became how to fix these shortcomings while maintaining a simple design.

To avoid the linear sliding motion of the plunger a parallel blade flexure design was adopted. Instead of a baffle-type dust seal, a felt seal was used. This was much easier and smaller to implement and also minimized any friction in the system. To protect the limit switches they were placed on their side and actuated via a ramp. To protect against side loads, caging features were implemented and, in the case of the MI contact sensor, a flexible pushrod would bend before breaking under side loads. An improved design is illustrated below in Figure 10.

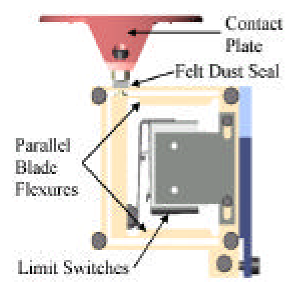

Figure 10. MB Contact Sensor

The dust cover was then refined to make it simpler. It was decided that the labyrinth was too complicated and could get jammed with dirt so it was simplified as well. Since the o-ring would probably get very stiff at cold temperatures, and such an airtight seal was unnecessary, the o-ring was removed from the design. The design was changed to have two faces (of dissimilar material) pressed against each other. The new design for the dust cover is illustrated in Figure 11.

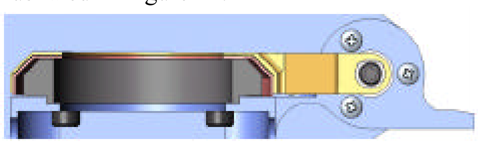

Figure 11. New Dust Cover Design (closed)

After numerous iterations, the final designs for the instrument mechanisms met all requirements efficiently and effectively.

Analysis

Throughout the design process, significant effort was made in analysis and testing to guarantee the final design was as robust as possible. As opposed to projects where the design is nearly finished before being handed to the analyst, the design and analysis (and even some testing) of these mechanisms were done concurrently, and often by the same engineer designing the parts. This allowed several iterations on the design to be done in a short amount of time, providing confidence that the best design had been chosen.

Actuation Dynamics

One of the most important studies was that of the actuation dynamics of the contact sensors. The amount of force necessary to trigger the limit switches and the precision and repeatability with which they triggered was very important. Ensuring sufficient stroke was also important. In addition, each limit switch has some hysteresis so there must be sufficient stroke to allow the limit switch to release after being removed from the target. The return force must also be enough to allow the limit switch to release after a long life in a cold and dusty environment. Figure 12 shows the predicted (worst-case) force vs. displacement of the contact sensors.

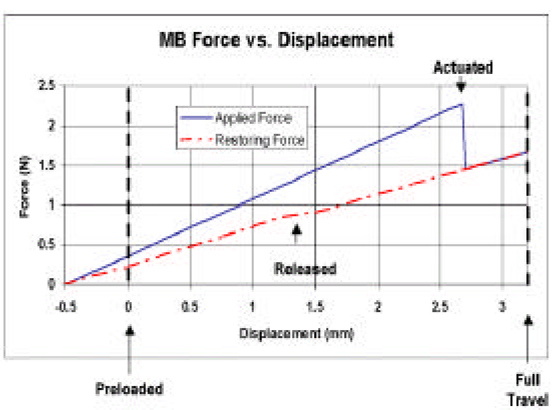

Figure 12. Contact sensor force vs. displacement

It was also necessary to show that the contact sensors would actuate at various angles and side loading conditions. This was a simple analysis for the MB contact sensor, but considerable effort was put into analyzing how the flexible push rod of the MI contact sensor would behave. The analysis showed that, under normal operating conditions, the limit switch would actuate before the push rod would bend or buckle. Even with side loads greater than those expected during normal operations, the push rod would simply deflect to the side some with the limit switches actuating very soon thereafter. Although the analysis showed that the push rod would perform adequately, the system was complex enough that we decided to perform tests of several different push rods to verify the push rod design.

Thermal

Temperature fluctuations did not put undue stress on any of the parts, but they were a factor to consider in tolerances and clearances. Brittle fracture of the push rod at cold temperatures was also a concern. This was very hard to analyze because the ductile/brittle transition point depends upon the amount of martensite formed in the push rod when it is cold worked. Since it was difficult to determine how much the material was cold worked, testing became the best means to verify the push rod would not fracture at cold temperatures. This testing is described in further detail later in the paper.

Motor Performance and Hard Stops

The main analysis for the dust cover was the motor analysis. Because the motor was being used on other MER mechanisms and very similar motors had been specified for previous JPL missions, much testing and analysis had already been done on the motors. Additional analysis was performed to show that the motor would not damage itself when running into the hardstops at each end of travel and to verify the detent torque of the motor would be enough to hold it closed during launch and landing.

Testing

As alluded to earlier, some testing was done concurrently with the design and analysis. Other tests were performed on the individual mechanisms after they were assembled. These tests were an effort to recognize potential problems as early as possible. In addition to these tests, functional testing of the mechanisms was done in conjunction with the IDD level functional testing.

Thermal Cycling

The contact sensors have the potential to be actuated several hundred times at cold temperatures on Mars, so thermal life cycle testing was done on each actuator. Although the number of cycles these mechanisms will experience is much less than what they are rated for, the extreme temperatures and the 'fly what you test, test what you fly' philosophy made it prudent to conduct life cycle testing at cold temperatures to see if any degradation in performance was noticeable. The contact sensors were taken to -120°C, allowed to soak, and then actuated 500 times each. The force and stroke to actuate and unactuate were recorded for each of the 500 cycles. No change in performance was noted.

Force/Stroke

Additional force and stroke measurements were recorded at ambient temperatures before and after vibration and thermal vacuum testing to see if any changes occurred. No changes in performance were noted.

Brittle Fracture

As mentioned earlier, the ductile brittle transition of the push rod was of some concern and analysis alone was not enough to convince us that the push rod would not break so some simple tests were performed. The push rod was submerged in liquid nitrogen (-196°C) and, while submerged, bent to a 90° angle. No signs of brittle fracture were present and it was determined that the push rod material could easily handle the necessary side loads at cold temperatures without breaking.

Motor

Most of the low level motor testing was done at Aeroflex but several functional tests of the motor were performed once it was integrated to the rest of the mechanism. These tests included running the motor at -55°C and +45°C in the thermal chamber at ASI, running the motor before and after vibration testing, and running the motor at -55°C and +45°C at Mars pressure in the thermal/vacuum chamber.

Vibration

After being integrated to the IDD, these mechanisms underwent additional functional testing as part of the IDD system level tests. The first of these tests was vibration testing which included sine burst and random vibration (Figure 13).

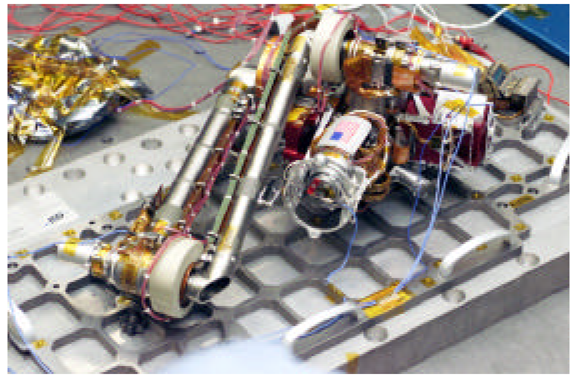

Figure 13. Vibration testing

None of the mechanisms were actuated during vibration testing but they were tested after vibration and performed nominally.

Thermal/Vacuum

The final test performed on these mechanisms was thermal/vacuum testing, which also took place as part of the entire IDD system level testing. The mechanisms were operated at -70°C (-55°C for the motor) and +45°C at Mars pressure (5-10 Torr). A picture of the IDD in the thermal/vacuum chamber is shown below in Figure 14.

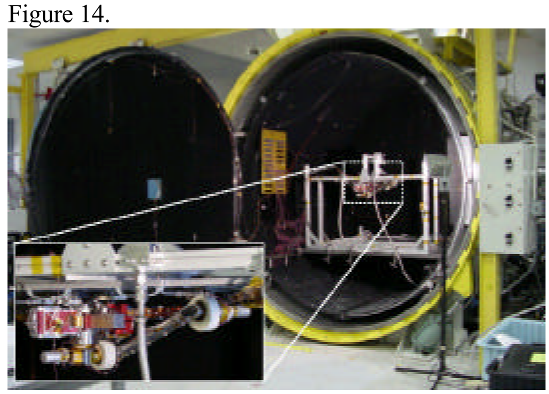

Figure 14. Thermal vacuum testing

Integration

The first set of hardware, the Engineering Model, was delivered to JPL on 6/10/02. This hardware was integrated with the Flight Software Testbed without incident. The F1 IDD, along with the F1 contact sensors and dust cover, were delivered 8/16/02 and the F2 hardware was delivered 10/11/02. The instrument mechanisms were successfully integrated to the flight hardware at JPL as shown in Figure 15.

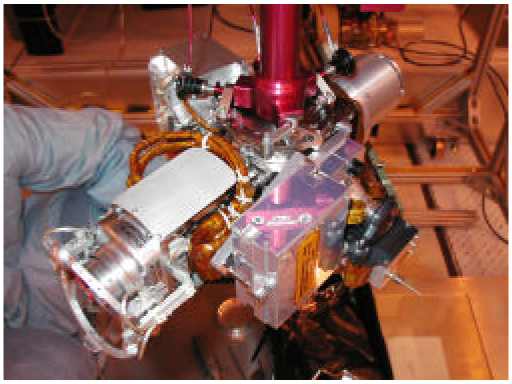

Figure 15. Instrument mechanisms integrated to their instruments

Lessons Learned and Conclusion

Lessons Learned

Development of these mechanisms has provided many lessons learned:

- Don't underestimate the complexity of something simple in concept. Designing a low-force actuator that doesn't jam in a dusty environment takes effort. Actuating with a long stroke along the desired axis while withstanding side loads is non-trivial.
- Consider a sensor with no moving parts. Heritage components drove this design but future designs should consider using strain gauges, piezoelectric, or optical sensors. It is still possible to meet the long stroke requirements with such systems by using a single moving part or relying on the flexibility of the system as a whole.
- Keep the big picture in mind, especially when the design involves the science instrumentation. It is easy to focus on the design/engineering without considering the science in detail. Don't assume others are considering the big picture. Get to know the science and the scientists. Understand that the science tends to change and evolve requiring more flexibility
- Interfaces are critical. This seems obvious, but it is often a problem on big projects with parts coming from scientists, universities, and engineers within multiple organizations (and multiple countries). ICD's are not always correct and there are often differences between engineering models and flight units that are supposed to be identical.
- Doing a simple test is often worth the effort. Determining that brittle fracture of the push rod was not a problem is a good example of this. That said, make sure to consider brittle fracture in the first place, especially on parts that are cold worked.
- Small mechanisms demand detailed tolerance studies. All CTE and machining tolerances must be taken into account as parts get smaller because clearances are typically very small.
- The limit switches in these mechanisms can easily be used improperly. Do not implement a design that allows the limit switch lever arm to be driven too far. Take the hysteresis of the switch into account. Allow for adjustments.
- Consider motor hardstops carefully. If a hardstop is placed too close to the axis of the motor it may be required to react forces it was not designed to take.
- Felt seals are often a good solution because of their simplicity and low profile. However, it is difficult to get them cut in very small shapes and tight tolerances are not achievable.

Conclusion

The MER rovers launched in June of 2003, and will land on the Martian surface in January 2004. The three mechanisms described in this paper will help MER accomplish its mission by protecting the instruments and, at the same time, allowing the instruments to be positioned on a target very precisely. This paper illustrates the challenges involved in developing mechanisms for Mars and the details of contact sensors and dust covers for deep space missions. As was shown, even seemingly straightforward mechanisms require significant effort to develop and there are plenty of potential pitfalls along the way.

References

1. *Mission to Mars* 2001, Artwork by Danial Maas.
2. Squyers, S. 2001. Retrieved April 10, 2003 from Cornell University, Athena, Mars Exploration Rovers Web Site: http://athena.cornell.edu/the_mission/instruments.html
3. Farguson et al. 2001, *Mars Exploration Rover Project, Environmental Requirements Document*, NASA/JPL
4. Breckheimer, E. 2003, *Mars Exploration Rover Project, Flight System Requirements Document*, NASA/JPL
5. Desai, R. & Miller, D. 1998. *A Simple Reactive Architecture for Robust Robots*, NASA/JPL
6. Mishkin et al. 1998, *Experiences with Operations and Autonomy of the Mars Pathfinder Microrover*, NASA/JPL

Back to Contents