MSL's Widgets: Adding Robustness to Martian Sample Acquisition, Handling, and Processing

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Abstract - *Mars Science Laboratory's (MSL) Sample Acquisition Sample Processing and Handling (SA-SPaH) system is one of the most ambitious terrain interaction and manipulation systems ever built and successfully used outside of planet earth. Mars has a ruthless environment that has surprised many who have tried to explore there. The robustness widget program was implemented by the MSL project to help ensure the SA-SPaH system would be robust enough to the surprises of this ruthless Martian environment. The robustness widget program was an effort of extreme schedule pressure and responsibility, but was accomplished with resounding success. This paper will focus on a behind the scenes look at MSL's robustness widgets: the particle fun zone, the wind guards, and the portioner pokers.*

Keywords: Mars Science Laboratory (MSL); Particle Fun Zone (PFZ); Vertical and Horizontal Portioner Poker; Wind Guards; Wind Tunnel Testing, Robustness Widgets.

1 Introduction

The Martian environment has never proven to be fully predictable and has held many surprises for spacecraft, destroying or even severely crippling many. In this respect, the Mars Science Laboratory (MSL) project embarked on a path to tackle the harsh Martian environment. An analysis was performed which identified areas of the Sample Acquisition Sample Processing and Handling (SA-SPaH) system where the unknown characteristics of the Martian environment posed significant risk to the robustness of the overall system. While the basic elements of the robustness widgets had been discussed as early as August 2007 (see Figure 1), the decision to take the steps to flight for these was not made until late December 2010. In order to be incorporated into MSL, the widgets had to be designed, fabricated, and tested by late May 2011. In those scant five months, the team had to go from cartoon sketches on napkins and previously defined keep-in zones to fully flight qualified elements. This process included developing sufficient understanding of how the widgets would be used by the rover such that we were not endangering other functions. In the case of the Observation Tray, which later became incorporated into the widget named the Particle Fun Zone (PFZ), this process was largely one of ensuring access by the sample-bearing tools. At the other end of the spectrum, the Wind Guards required an extensive test program inside a wind tunnel that simulated the conditions of Mars.

Figure 1. Early concepts of the Observation Tray, which is mounted on the PFZ, included a simple flat plate (left) as well as a faceted "bug-eye" (right) that presented a horizontal surface even when the rover was tilted.

In the end, we were in a position that required that the widgets be installed onto the rover before testing was complete to buy back time. This came with the understanding that they may need to be removed prior to launch on November 26th, 2011, if the ensuing testing revealed that their presence posed any unforeseen risk to the system.

2 Robustness Widget Overview

The robustness widgets were conceived to essentially tackle the unpredictable nature of the Martian environment. Below is a picture that highlights the location of each robustness widget's respective location on the MSL rover.

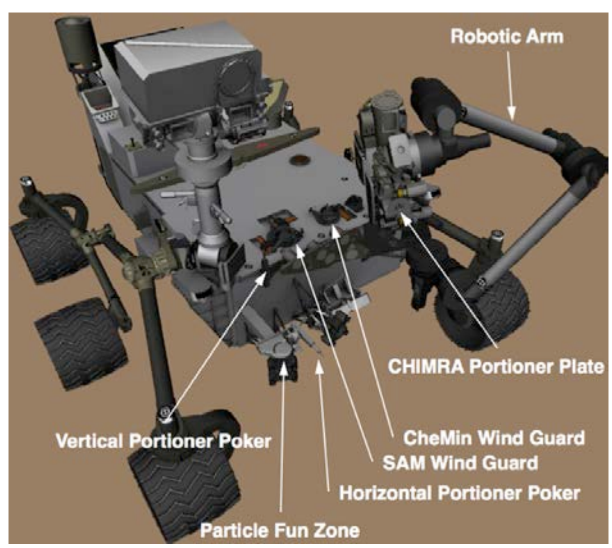

Figure 2. Picture depicting the location of each robustness widget on the MSL rover.

The Particle Fun Zone (PFZ), which includes many components, was conceived to investigate sample characteristics before ultimate ingestion in MSL's laboratory instruments, the Sample Analysis at Mars (SAM) and Chemistry and Mineralogy (CheMin) instruments. The Portioner Poker was conceived to eliminate the possibility of clogging the smallest bottleneck, the portioner tube, of the SA-SPaH system's Collection and Handling for In-Situ Martian Rock Analysis (CHIMRA) tool. The Wind Guards were conceived to mitigate the risk of wind adversely affecting sample delivery to the SAM and CheMin laboratory instruments for analysis.

3 Particle Fun Zone

MSL's Particle Fun Zone (PFZ), or sometimes referred to as the Sample Playground, is a small collection of geometric features designed to mitigate risk by allowing scientists to make quantitative and qualitative assessments of Martian regolith or rock sample quality prior to transferring acquired samples to MSL's laboratory science instruments, SAM and CheMin. This sample delivered to the different PFZ elements cannot be reacquired and is thus discarded. The PFZ's elements can be seen in Figure 3, and consist of one scientifically required piece of hardware, the Science Observation Tray, while the remaining geometric features were designed to help further assess the acquired sample. These are the Engineering Observation Tray, the CheMin Surrogate Funnel, the Soil Capture Plate, and the Dust Removal Tool (DRT) Scratching Posts. The PFZ also provides an interface for the Horizontal Portioner Poker, discussed in detail in a subsequent section. In addition to schedule pressures (PFZ concept to flight unit delivery in 4 months), the most time consuming aspect of the PFZ design was positioning each element to allow a safe interaction with the various tools on MSL's turret, the end effector of the robotic arm. PFZ elements were required to interact with the drill, the primary portioner of CHIMRA, the scoop of CHIMRA, the DRT, the Alpha Particle X-ray Spectrometer (APXS), and the Mars Hand Lens Imager (MAHLI). Dozens of configurations were studied and evaluated to minimize close clearances and avoid inadvertent contact between the robotic arm and other nearby hardware.

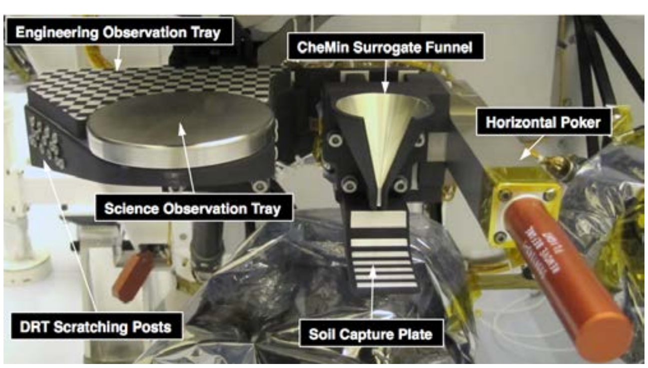

Figure 3. Particle Fun Zone Overview

3.1 Science Observation Tray

The Science Observation Tray (SOT) accepts soil samples from the CHIMRA tool which is mounted on the end of the robotic arm, and serves as the backdrop for the APXS. Because each of the 98 naturally occurring chemical elements emits a characteristic spectrum when irradiated, the SOT was made from commercially pure Titanium. The Ti spectral line can be easily removed from data when Martian samples placed on SOT are being analyzed for chemical composition by APXS. The SOT is also instrumented for temperature measurement.

Because the SOT is designed to be cleaned by the DRT (a rotating stainless steel wire brush), yet must also remain pure Ti, the SOT was subjected to a life test simulating 3x the number of desired cleaning cycles. The life test unit was then subjected to APXS irradiation to ensure that cross contamination had not occurred, and no stainless steel from the DRT was transferred to the SOT.

3.2 Engineering Observation Tray

The Engineering Observation Try (EOT) also accepts samples from the turret, and exists to provide a surface for making general soil quality assessments. Larger soil samples can be dumped from the scoop to make qualitative assessments regarding grain size, clumping potential, repose angle, etc. The laser ablated hard anodize coating provides a grid to enable optical volume determination of a soil sample using MSL's plethora of engineering and science cameras.

3.3 CheMin Surrogate Funnel & Soil Capture Plate

Clogging an instrument inlet funnel would severely diminish an important science capability. The CheMin Surrogate Funnel (CSF) replicates the material, geometry, and coatings of the CheMin inlet funnel, yet with a small cross section removed. Once sample from CHIMRA is deposited into the CSF, the MAHLI camera can be used to visually assess whether or not the CSF has been clogged. Engineers can use these observations to assess the clogging potential of a given sample inside the real instrument funnels. Additionally, the Soil Capture Plate (SCP) resides below the CSF, and provides visual confirmation that a sample deposited into the CSF did indeed pass through. The SCP also has a laser ablated hard anodize stripe pattern that provides slope graduations.

3.4 DRT Scratching Posts

The final PFZ element is the set of DRT Scratching Posts. This pattern of screw heads provides raised features to support an emergency DRT cleaning sequence. While the DRT is designed to only sweep dust, it is possible that the brushes encounter a clay-like material that could stick to the tool. Running the DRT brushes against these scratching posts would aid in the removal of such material. Astute observers may also notice that the DRT Scratching Post pattern doubles as a logograph, making tribute to a highly respected JPL engineer who passed during MSL's development.

4 Wind Guards

The SA-SPaH architecture, driven by the laboratory instrument requirements, generates fine particles for scientific analysis that are susceptible to wind. Thus, the Martian environment can pose a challenge for delivering samples of these fine particles from the robotic arm mounted CHIMRA tool to the top deck mounted laboratory science instruments, SAM and CheMin. Since the robotic arm mounted CHIMRA tool was designed to avoid direct contact with the deck mounted SAM and CheMin instruments to prevent hardware damage, sample must be dropped from the portioner tube approximately 20 mm above their respective inlets. Any wind that flows between CHIMRA and the inlets of the deck mounted laboratory instruments during this delivery event can easily disperse the sample into the Martian environment. This unfortunately would result in a loss of delivered sample to the laboratory instruments, and ultimately potentially groundbreaking science data.

Consequently, the wind guard widget was designed, implemented, and added to existing hardware to protect sample from the Martian wind during sample transfer to ensure most, if not all, of the samples are successfully delivered to the deck mounted laboratory science instruments for subsequent scientific analysis.

4.1 Wind Guard Hardware

The wind guard widget consists of two assemblies, SAM wind guard assembly and CheMin wind guard assembly, and one piece part, the CHIMRA portioner plate.

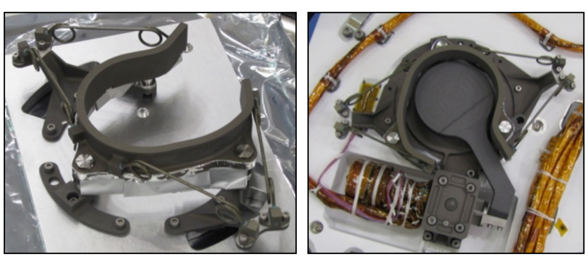

Figure 4. Pictured are the CheMin wind guard assembly (left) and CheMin wind guard assembly attached to the CheMin Inlet Assembly (right). The CheMin inlet cover opens to expose the instrument inlet.

The SAM and CheMin wind guard assemblies are mounted to their respective science instrument inlets on the rover top deck and form the bottom half of the wind barrier. Both assemblies have an aluminum piece part called the skirt that closely matches the contour of the SAM and CheMin inlets along with the swept volume created by the inlet covers. The skirt is suspended above the inlets by titanium spring wires, and the suspension of the skirt serves two functions: 1) the suspension allows for the skirt to deflect axially when in contact with the CHIMRA portioner plate, and 2) the suspension prevents the skirt from bottoming out against the rover top deck due to robotic arm inaccuracies when deflected axially. Additionally, guide pins are placed around the skirt at key locations to limit the skirt radial deflection. The last major piece is the aluminized Tedlar, which closes out the gap between the bottom of the skirt and the rover top deck. The aluminized Tedlar is soft enough to conform when the skirt is deflected, yet strong enough to block out wind.

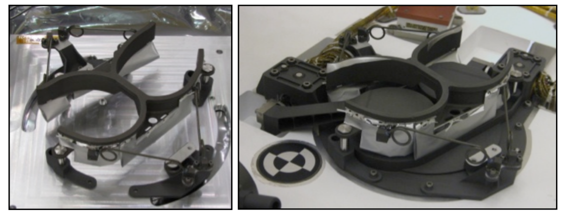

Figure 5. Pictured are the SAM wind guard assembly (left) and SAM wind guard assembly attached to the SAM Inlet Assembly (right). Either of the two SAM inlet covers can open to expose the instrument inlet.

The last piece of the wind guard widget is the CHIMRA portioner plate, which makes up the top half of the wind barrier. The CHIMRA portioner plate is attached to CHIMRA near the sample portioner tube and is designed to be as large as possible, radially, so that it can cover the inlets even with robotic arm inaccuracies.

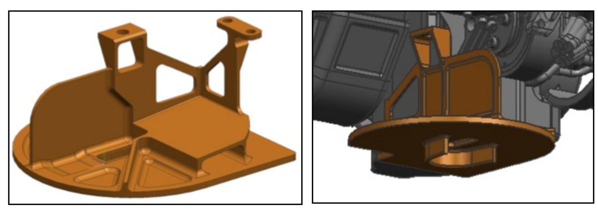

Figure 6. CHIMRA portioner plate (left) and CHIMRA portioner plate attached to CHIMRA's portioner box (right). The portioned sample is held within a portioner tube inside the portioner box for delivery.

Operationally, when the robotic arm is positioned directly over the SAM or CheMin inlet during sample delivery, the CHIMRA portioner plate is above the skirt of the wind guard assembly. With the combination of the CHIMRA portioner plate and the wind guard assembly, the inlet and the sample is protected from any wind flow during sample transfer. Although the design does not completely seal off the sample transfer path from the Martian environment, the design still provides some protection that would not otherwise be there.

4.2 Portion Tube Modification

To deliver sample into a laboratory instrument, MSL is required to perform an intricate dance with its SA-SPaH system. Through the use of the robotic arm, CHIMRA processes ingested sample acquired from either the scoop or the drill, sieves the sample with a 150 micron sieve, and then portions the sample for eventual delivery to the SAM or CheMin laboratory instruments. But right before delivery to the laboratory instrument of interest, the sample is portioned within CHIMRA's portioner tube and the robotic arm positions CHIMRA above the laboratory instrument inlet. The instrument inlet cover opens, CHIMRA is then lowered by the robotic arm until the CHIMRA portioner plate docks with the wind guard right above the instrument inlet. Once this docking occurs, CHIMRA subsequently opens its portioner door, exposing its portioned sample and vibrates the sample residing within the portioner tube to finally deliver the sample into the laboratory instrument inlet. Below is picture depicting the sample delivery configuration over the SAM inlet.

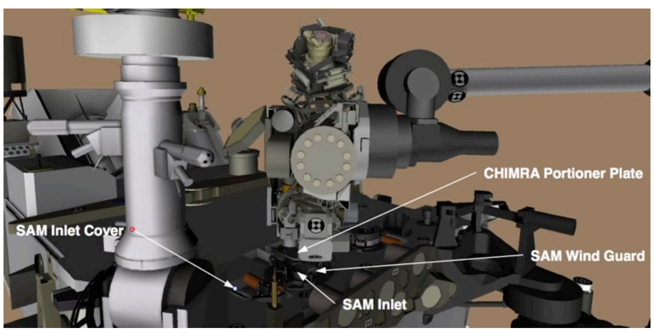

Figure 7. Here CHIMRA is positioned above the SAM inlet by the robotic arm and docks with the SAM wind guard to deliver portioned sample into the SAM inlet.

During the development of the wind guard hardware, a significant analysis was performed on the robustness of MSL's delicate sample delivery process. Amidst this, a risk was identified that the original portioner tube holding the necessary amount of sample volume to CheMin or SAM was insufficient mainly due to wind dispersion susceptibility. The main fix to this wind dispersion susceptibility was indeed the wind guards, but the team decided to additionally implement a portioner tube modification on the flight hardware literally months before launch to further reduce this wind dispersion susceptibility.

Upon extensive analysis it was decided to increase the portioner tube diameter to allow more sample volume to be delivered, and also implement a taper to the portioner tube itself to make the sample more likely to come out all at once, further increasing the delivered sample's ballistic coefficient. Below is a figure depicting the volume increase and the tapering that was implemented in CHIMRA's portioner tube.

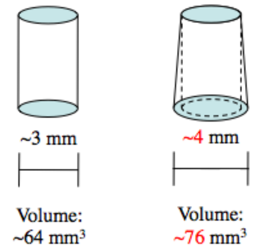

Figure 8. CHIMRA portioner tube's volume was increased from approximately 64 mm^3 to approximately 76 mm^3. In addition, a taper was implemented to promote the sample to fall out all at once in a clump during sample delivery.

Through relevant testing, it was observed that the tapered portioner tube induced granular dilation at the bottom of the tube. Therefore with the taper in place the sample at the bottom of the tube experiences lower density than the sample at the top, effectively allowing the sample to be delivered as a more coherent clump compared to the original non-tapered cylindrical tube.

4.3 Wind Tunnel Testing of Wind Guards

The development of the MSL SAM and CheMin wind guards required an aerodynamic performance assessment to justify their implementation on the vehicle. This was accomplished through a combination of subscale and full-scale wind tunnel tests at CalTech and NASA Ames. The goal of the subscale testing was to identify the effectiveness of the wind guards at reducing flow velocities over the SAM and CheMin inlets. This information was then used to determine worst-case scenarios for the full-scale wind tunnel testing. The full-scale test ran a simulation of the sample delivery process between the CHIMRA portioner box and the inlets in a scaled Martian wind environment, and measured mass of material collected in the inlets. With data collected from both test configurations, the decision was made to fly MSL with the wind guards installed on the inlets. Additionally, the test data provided guidelines to the operational use of the SAM and CheMin inlets on Mars.

4.3.1 Non-dimensional scaling

The identification and scaling of parameters between Earth and Mars is critical to attaining meaningful information from wind tunnel testing. For the subscale CalTech tests, which were only looking to quantify the reduction in flow velocity over the SAM and CheMin inlets, the primary scaling factors were Reynolds Number and Mach Number. With a $1/8^{th}$ scale rover model and a target tunnel velocity of 1.5 m/s (15 m/s on Mars), the corresponding Reynolds Number was approximately 500 and the Mach Number was approximately 0.06. Since the flow regime of interest was considered to be incompressible, the primary driver was the Reynolds Number. For the full scale testing, which involved the dynamics of particles in a flow, the primary scaling factors were Reynolds Number, Inertia Parameter, Froude Number, and Knudsen Number. The variables necessary to match these scaling factors simultaneously were drop test particle diameter, particle density, tunnel velocity, and tunnel static pressure. Based on surface composition data from Pathfinder, Saddleback Basalt sample with diameters less than 150 micron were identified as the most applicable drop test material. Then the NASA Ames Planetary Aeolian Laboratory's wind tunnel was used in order to match velocity and static pressure requirements. Through the use of the adjacent Thermophysics Facility's steam vacuum system, the ambient pressure in the tunnel was decreased to the target 1000 Pa and then their open circuit wind tunnel provided the target 25 m/s flow.

4.3.2 Subscale Rover Wind Tunnel Testing

Wind guard effectiveness testing at the SAM and CheMin inlets was performed at the CalTech Lucas Adaptive Wall Wind Tunnel. A 1/8th scale SLS model of the Rover with multiple SAM and CheMin inlet and robotic arm configurations were mounted within the tunnel test section on its 360° turntable. Within the opening of the inlets, two axis hot wire anemometers in the horizontal plane of the tunnel were mounted to measure the magnitude of wind velocities at these locations, which coincided with where delivered samples would be exposed to ambient Mars winds. With the test conditions identified through the non-dimensional scaling effort, each rover configuration was exposed to 1.5 m/s winds at 360° around the vehicle. The data was used to characterize which rover wind angles of attack would result in minimum and maximum wind conditions at the 3 inlets. Since a full 360° range of sample drop tests for every sample port configuration was time and cost prohibitive, the worst case test conditions were used to select where to begin in full-scale wind tunnel testing.

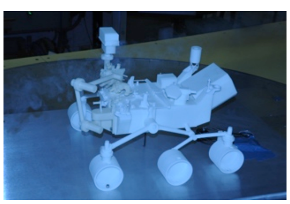

Figure 9. 1/8th scale rover model in CalTech Wind Tunnel.

The data also provided a quantitative way to assess the benefits of the wind guard over the non-wind guard configurations.

4.3.3 Full-scale Rover Wind Tunnel Testing

CHIMRA sample sample delivery effectiveness to the SAM and CheMin inlets was performed at NASA Ames' Planetary Aeolian Laboratory's wind tunnel. A full-scale mockup of the rover top deck within a 23" radius of the inlets was installed within the test section on a rotary table. Then a balance was installed within each of the inlets to measure the mass of Basalt successfully transferred into the respective inlets. Above the deck, a gantry was used to support a three axis controlled mockup of the CHIMRA portioner box with a functioning Basalt sample dispenser mechanism. This device had the capability to deploy up to 200 samples weighing approximately 0.05g each.

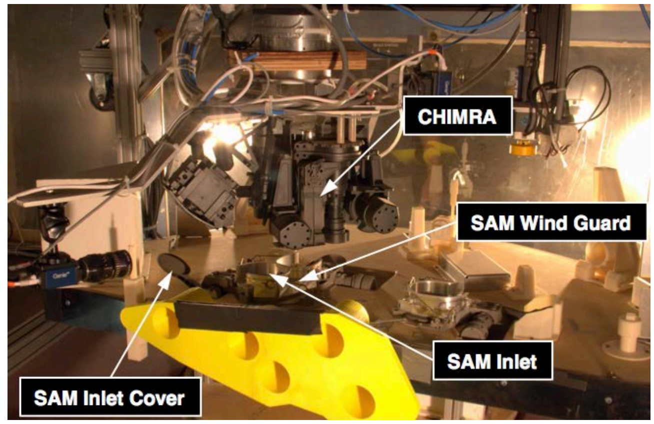

Figure 10. The full-scale mockup of rover top deck pictured inside the tunnel with CHIMRA positioned above the SAM inlet for delivery.

Three cameras were used to monitor the sample delivery qualitatively. The automation of this setup was critical due to the 1 hour period necessary to pump the ambient pressure in the wind tunnel down to low vacuum (~1000 Pa), and test durations of 30-60 minutes. Prior to testing, the Basalt samples were baked out to remove volatiles and then it was sieved to isolate particles 150 microns and less. This material was then loaded into the sample dispenser hopper and numerous deployments were performed at 1 ATM to gauge the average mass of material released. Once this was completed, the chamber was pumped down to 1000 Pa, the wind tunnel was ramped up to 25 m/s, and then the desired rover angle of attack was set before samples were released into the inlets. Multiple drops per site were performed due to difficulties associated with dispensing the Basalt near the vapor pressure of water. Over the course of testing, thirteen configurations of the inlets with and without wind guards were investigated based on the points of interest derived from the subscale testing. Quantitative and qualitative information from both subscale and full-scale testing were used to extrapolate the performance of the sample transfer process. These results indicated a comparable ability to transfer a majority of the soil samples in a conservative low ballistic coefficient stream of particles. The edge was given to the wind guard configuration primarily since it minimized horizontal winds in a majority of rover wind angles of attack, which reduced the dispersion cone of the Basalt in most cases. The test data additionally provided the information necessary to optimize the amount of Basalt transferred to the inlets in the operational Mars environment.

5 Portioner Poker

The primary sample delivery method for both scooped regolith and drilled rock powder is through a 4 mm diameter tube called the portioner tube as mentioned earlier. The long and narrow aspect ratio of this tube represents a unique clogging concern for the SA-SPaH system. Clogging of this portioner tube would severely hinder the sample delivery to the laboratory instruments. While the SA-SPAH already has built in, and effective, clog clearing functionality, the importance of the portioner tube, as it is the smallest bottleneck of the system, was such that an additional device was added to further enhance robustness – the portioner poker. In the final configuration there are two portioner pokers mounted on the front chassis of rover, each identical except in orientation and mounting configuration. These can be seen in figure below.

The portioner poker is a single-degree-of-freedom, spring-loaded plunger with a high strength steel poker pin on the end. It is used to break through and push out any clogged sample within the portioner tube. Due to severe schedule pressure, great effort was taken to keep the device as simple as possible. The single degree of freedom, an axial spring, was required because the portioner tube target is smaller than the guaranteed positioning accuracy of the robotic arm; this means that the pin needs to compress out of the way if – or rather, when – it misses the portioner tube. Additionally, the poker incorporates a high-efficiency particulate air (HEPA) filter through which the interior cavity is vented and a thin polytetrafluoroethylene (PTFE) wiper at the sliding interface between the plunger and housing.

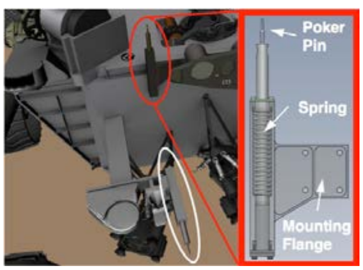

Figure 11: Location of the vertical and horizontal portioner pokers on MSL (left). Also the vertical poker is exploded for a detailed view of the primary portioner poker (right)

One of the most challenging aspects of the design was accommodating the limited *absolute* placement accuracy of the portion tube by the robotic arm. Potential side loading of the pin precluded using a "nest" of many closely spaced, and smaller, pins that could cover the entire placement zone. Extremely tight packaging requirements and the lack of available launch-locking actuators made a multi-DOF, self-centering, pin very difficult to implement. This challenge was solved by taking advantage of the robotic arm's highly precise relative motion capability. A standardized "raster scan" operation was designed in which the robotic arm makes a series of small, highly precise relative motions each followed by an axial plunge against a laterally rigid poker. The raster scan was designed to guarantee that at least one of the plunges would align the portioner tube with the portioner poker pin. The majority of the plunges, however, would miss the tube in which case the poker would plunge out of the way harmlessly. As additional precaution, the preexisting load sensing and limiting capability of the turret avionics is enabled during the portioner tube clearing operation. If the poker jams and does not plunge out of the way for any reason during the raster scan this load limiting allows the robotic arm to stop motion, reverse, and move onto the next raster scan location without faulting the entire operation.

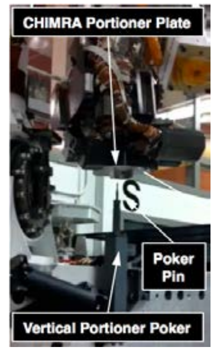

Figure 12: Testbed photograph of the vertical portioner poker. Here CHIMRA is being lowered so that the poker pin may puncture through a clogged portion tube.

Although it needs to plunge out of the way in case of a "miss", the portioner poker also needs to generate sufficient force at the pin tip to puncture through any realistic clog, including, as a worst case, moist sample that has frozen in the tube. A test program using a variety of powdered rock types and moisture levels packed and frozen into portioner tubes was conducted to identify the bounding force required to clear a clog. The force required to puncture through this clog was measured and the results determined the target axial spring load on the pin at its minimum actuated stroke.

The portioner pokers are simple devices that fit within the existing free volume and utilize existing mounting features. They were able to be implemented on a greatly accelerated schedule near the end of the program and have added considerable robustness to a critical sample delivery function.

6 Conclusions

The identification of risk played a fundamental role in selecting the proper widgets to build and fly. Without doubt, the PFZ, the wind guards, and the portioner pokers all increased SA-SPaH's robustness. In order to reach a flyable state each piece of widget hardware went through a rapid and exhaustive design, build, and test phase. Through the intense hard work of the widget team every piece of hardware identified was successfully flown to Mars and thus incrementally improved the robustness of MSL's SA-SPaH system. On August 5th, 2012 MSL landed on the surface of Mars eager and curious to explore the harsh but enticing Martian environment. Without these robustness widgets this exploration would have certainly been a more risky proposition.

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Acknowledgements

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.