MARS SCIENCE LABORATORY ROBOTIC ARM

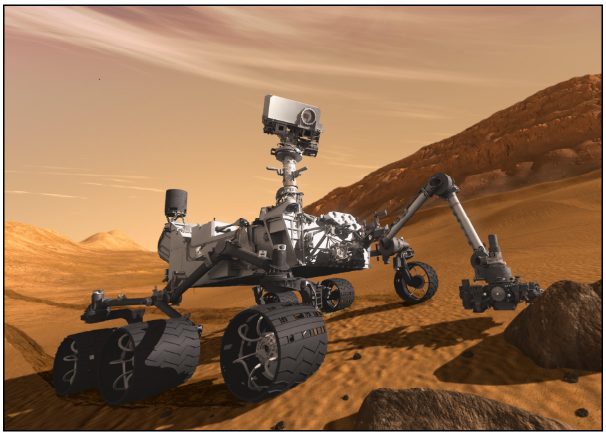
Principal Author Rius Billing[1], Co-Author Richard Fleischner[2],

*[1]MDA Information Systems, Inc. Space Division, Robotics and Mechanisms,
1250 Lincoln Ave, Pasadena, CA 91103, USA, Email: rius.billing@MDAUS.com*
*[2]MDA Information Systems, Inc. Space Division, Robotics and Mechanisms,
1250 Lincoln Ave, Pasadena, CA 91103, USA, Email: richard.fleischner@MDAUS.com*

ABSTRACT

The Mars Science Laboratory Robotic Arm (MSL RA) is a critical, single–fault-tolerant mechanism in the MSL science mission that must deliver 5 of the rover's 12 science instruments to the Martian surface.

This paper will describe the design, build, and test methodology which evolved as the science payload matured over the course of the 4-year project. Lessons learned based on the EM and Flight unit testing will also be discussed.



1. INTRODUCTION

The Mars Science Laboratory mission is NASA's most ambitious science mission to another planet. MSL incorporates many lessons learned from the Pathfinder mission and Sojourner rover, the twin Mars Exploration Rovers, and the Phoenix Lander.

The Robotic Arm will be a key part of the Sample Acquisition, Processing, and Handling (SA/SPaH) system. The RA will be responsible for accurately placing the 5 turret-mounted instruments on their respective targets and acquiring samples. These instruments are a drill capable of capturing rock samples, MAHLI camera, Dust Removal Tool (DRT), Alpha Particle X-Ray Spectrometer (APXS), and CHIMRA. After a sample has been acquired by the drill or the scoop on the CHIMRA, the sample will be transferred to the CHIMRA processing unit and use gravity, assisted by induced vibration, and coordinated movement of the RA to process samples to deliver to the rover-mounted science instruments for soil tests.

The MSL rover will carry the most advanced payload of scientific gear ever used on the Martian surface, a payload more than 10 times as massive as those of earlier Mars rovers. Its primary scientific goal will be to investigate whether past conditions had been favorable for microbial life and to accomplish acquisition and handling while preserving clues in the rocks about possible past life.

Over the last 10 years, MDA-US (formerly Alliance Spacesystems, Inc) has designed and built every robotic arm successfully deployed and operated on the surface of Mars. The IDD robotic arms from the Mars Exploration Rover have been working on the twin rovers Spirit and Opportunity since 2004 and each played a large role in the discovery of the existence of water on the Martian surface. The Phoenix robotic arm was successfully deployed to the Martian surface in 2008 and was instrumental in the discovery of frozen surface and subsurface water.

The MSL robotic arm program leverages the experience garnered from the MER and Phoenix programs to produce an instrument capable of surviving a lifetime 7 times longer than any previous in-situ planetary mission.

The main attributes of the MSL Robotic Arm are:

- 5 degrees of freedom
- 2.2 meters outstretched length from base to center of instrument turret
- 67 kg mass without turret instruments
- 5 turret instruments with mass of 34 kg
- Electrical cabling system with 920 signals traversing the length of the arm
- Two dual-use caging mechanisms capable of surviving landing loads of over 20g, passively re-stowing the RA after deployment, and surviving rover driving loads of 8g
- Capable of surviving temperature range of -128ºC to +50ºC and operating within a temperature range of -110ºC and +50ºC

Because of the complex nature of the mission and the extended development schedule, there were several major changes to the MSL architecture passed down from NASA/JPL that affected the design at a late stage:

- A change throughout all rotary actuators from dry to wet lubrication because of severe life-limiting issues found in early actuator testing
- A payload mass increase on the RA instrument turret from 15 kg to 34 kg, that required a redesign of restraint and caging mechanisms for launch and traverse
- An increase in electrical system complexity that required the cabling system to carry more than 300 new signals to the reconfigured instrument cluster

The mission's duration is 687 Earth days, over 7 times longer than any planetary rover mission in the past. Life tests were therefore required and completed to assure satisfactory performance over this life time. Testing included life cycle tests for the caging mechanisms making up the launch lock and restow system. Bearing life tests were also conducted to prove the validity of the dry lubrication used on the moving parts of the cable management system. A full suite of environmental tests were conducted as well, including vibration testing and thermal vacuum testing.

2. CONFIGURATION CYCLE

The typical configuration cycle for a planetary robotic arm is initially comprised of a plethora of tasks that help refine the configuration and specifications up to the Preliminary Design Review (PDR). There were 10 mechanical configurations under consideration, some serial and some in parallel that were reviewed and analyzed for the following criteria:

- Range of Motion (ROM)
- Workspace access (slimness and dexterity)
- Cable layout down the length of the robotic arm
- Loads generated at launch and during rover traverse

Each distinct configuration generally has advantages and disadvantages made apparent through detailed examination, but over the course of development an optimized configuration arises which fairly equally distributes performance associated with each of the four criteria. During this development process, each configuration is adjusted until ranges of motion and workspace access are maximized and that the cabling path is electrically and topologically suitable. Throughout this optimization process system loads cases are run on a fairly detailed model of the configuration which incorporates structural, actuator, and launch mechanism compliances.

The system loads cases are compiled and arranged in load groups corresponding to the various subsystems comprising the robotic arm. As far as design inputs are concerned, these load groups are considered the current best understanding of what the launch, landing, and operation loads will be throughout the arm's subcomponents. For the MSL RA, 12 loading scenarios were used as inputs to the system loads model. The initial launch loads were derived from the general specifications of launch vehicle Mass Acceleration Curves (MAC); random vibration analysis; conservative landing loads; the operational loading from Earth operations in 1g; rover-induced loads from driving; and loads required to preload the various turret-mounted instruments against the Martian surface. Loads due to inadvertent actuation of the robotic arm while still locked in its caging mechanisms were also considered. Due to early uncertainty in the design of the rover and joint actuators, many different combinations of variables were used to span the anticipated ranges of stiffness. Many load cases were run incorporating all possible permutations of stiff/compliant rover structure, stiff/compliant actuators, etc. The highest case-independent loading local to each arm subsystem was then segregated and compiled into an overall worst-cast case scenario for the arm. This loads scenario was then used as the

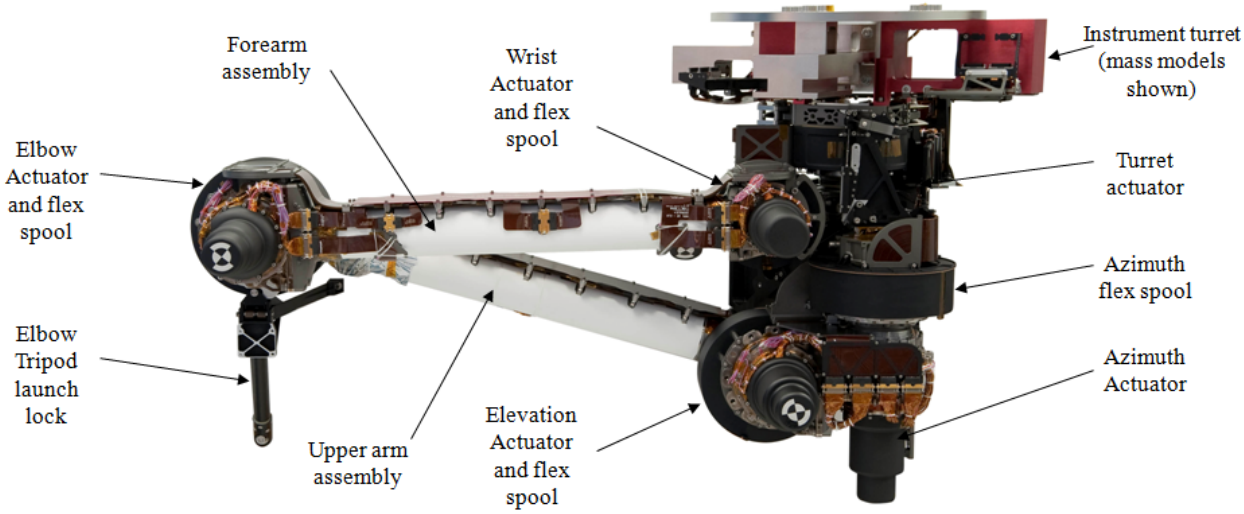


Figure 1, MSL Robotic Arm

design driver for the arm structure and caging mechanisms. As the design matured these 12 different cases were re-run and the results were used to further refine the design.

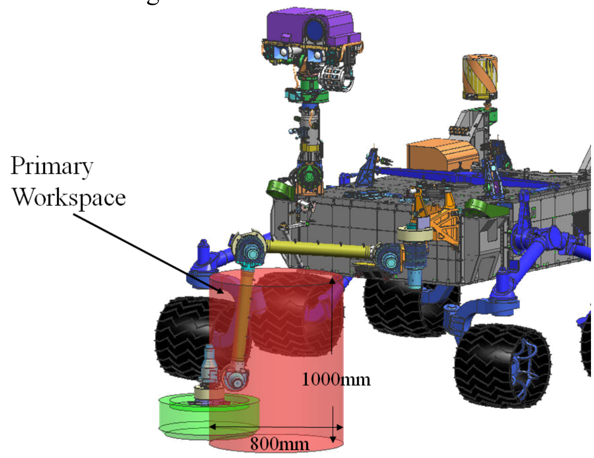


Figure 2, Primary workspace

In addition to structural considerations, the robotic arm must meet its positioning requirements for targets inside an assigned volume called the “robotic arm primary workspace”.

The workspace, as shown in Fig. 2, was defined in the requirements as “an upright cylinder 80 cm diameter, 100 cm high, positioned 105 cm in front of the front body of the rover, and extending to 20 cm below the surface when the rover is on a smooth flat terrain.” An analysis was performed to ensure that a high percentage of the workspace could be reached and preload could be applied to the instruments at almost any angle the robotic arm is capable of positioning them. This analysis typically has over a million points of contact resulting from calculations which take into account all possible joint angles.

Typically, after the PDR the configuration development cycle stops and the detail design phase begins, but because the MSL mission was still maturing MDA-US was presented with a few new opportunities. The baselined soil processing mechanism previously mounted elsewhere on the rover was now relocated on the arm’s instrument turret. This change had multiple effects on the RA, most notably that the turret-mounted instruments mass increased 126% from 15 kg to 34 kg, a 25% overall increase for the RA system. Additionally, this relocation of electromechanical components increased the cabling wire count from 620 to 920. This change required another round of system loads and workspace analysis to be carried out because of the mass addition at the end of the RA. This in turn drove design iterations on the caging mechanisms and other structural parts. There was fortunately an earlier accommodation for a spare flex cable still available in the system.

The development cycle continued past the Critical Design Review (CDR) as well. This was due to the fact that the JPL-supplied actuators were not surviving life tests. The original plan for the entire MSL project was to develop mechanisms that did not require external heating due to the limited battery power on the rover. The actuators were therefore developed with dry lubrication in mind. Following the life-test failures, the actuators underwent a design change to incorporate wet lubrication as well as a material change from Titanium to Vascomax C250 steel. This change increased actuator mass from 5.7 kg to 7.8 kg each for the 3 large actuators, (elevation, azimuth, and elbow) and an increase from 3.0 kg to 4.2 kg for the 2 smaller actuators, (wrist and turret). This accounted for an additional 14% mass increase to the RA system. Another full iteration of the system loads cases was run and all piece part analysis was rechecked and verified with the new system loads.

3. SUBSYSTEM DESIGN

There are 4 basic subsystems to a robotic arm as designed by MDA-US. These are caging mechanisms, cabling system, structure, and actuators.

3.1. Caging Mechanisms

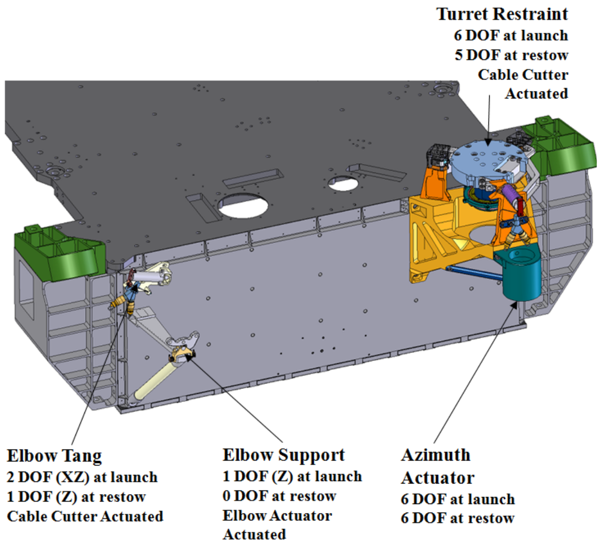


Figure 3, Caging mechanisms

Developing the caging mechanisms for a 5 Degree of Freedom (5 DOF) robotic arm mounted to a moving platform is an interesting design problem. The mechanisms have to survive launch and landing loads throughout the thermal environment and then release the RA to deploy for use. The mechanisms must also be able to passively stow and protect the RA during roving maneuvers. The caging system must also not over constrain and bind the arm during thermal transitions which vary, in the case of the MSL arm, from -128ºC to +50ºC (survival temperature range). This is very important because the rover front panel onto which the RA is mounted is Aluminum 7075 and the RA is primarily Titanium 6AL-4V, two materials which have vastly different CTEs. Fig. 3 shows the multi-DOF system designed to lock the MSL robotic arm for launch. The instrument turret is the single most massive subsystem of the arm and therefore must be fully constrained in 6 DOF at launch. The elbow of the RA is constrained only in the directions that are needed to protect the actuators and structure, with allowance for the arm to expand and contract relative to the rover front panel. A dynamic analysis is used to iterate which degrees of freedom must be locked out to protect the actuators and structure.

3.2. Cabling System

The cabling system developed for MDA-US robotic arms is unique in that it spans from the rover bulkhead to the instrument turret in one piece. The 10m long flex cables used are very mass and volume efficient and are an appropriate design solution when 920 signals must pass down a 5-DOF robotic arm. 22 connectors and 555 signals traverse the RA to the five discrete instruments on the turret. See Fig. 4 for the comparison of the round wire entering the RA to the flex cable on the RA. The shortest flex cable terminates at the azimuth and elevation actuators and is 2.8 m long. Fig. 5 shows the single cable path from Rover bulkhead to Turret connectors.

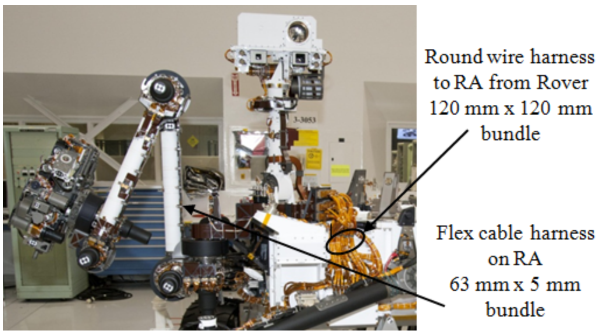


Figure 4, round wire bundle vs. flex cable bundle

Another advantage to the flex cable system is that each individual signal can be customized for its voltage and current requirements. The flex cable for the turret-mounted MAHLI camera is a 75 ohm matched impedance cable tailored for the video signals. Each flex cable, 8 in total on the MSL RA, contains 2 trace layers and two shield layers, one on both top and bottom. Noisy signals such as motor power can be isolated by arranging them away from quiet signals such as encoders or resolvers.

Because this robotic arm will be on a lengthy mission handling rocks and soils, it was required that the flex spools at each actuator be sealed from the Martian dust. The specific issue was that dirt could get between the layers of flex cable and over time abrade the outermost protective layer of the cable. This protection was accomplished with phenolic seals at each rotating interface entering and exiting the flex spools.

Two flex spools on the robotic arm required steel 4-point bearing be used to let the spool rotate with the joint. A moly disulphide (MoS2) dry lubricant was used in the bearing to allow it to function at the extreme cold temperatures of -128ºC without requiring a heater. A life test was performed and test results are shown in section 4.2.

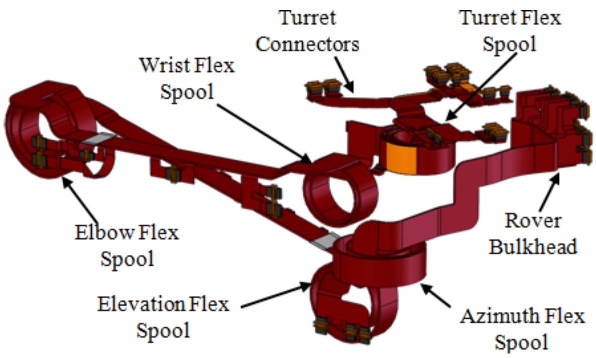


Figure 5, flex cable system

3.3. Structure

The structural members of the robotic arm are predominantly Titanium 6AL-4V for mass savings and CTE matching to the bearing steels and housings used in the actuators. The arm is mounted to the aluminum rover front panel to the aluminum shoulder bracket. There is an engineered transition interface between the aluminum shoulder bracket and the titanium output bracket which couples to the output shaft of the azimuth actuator as shown in Fig. 6.

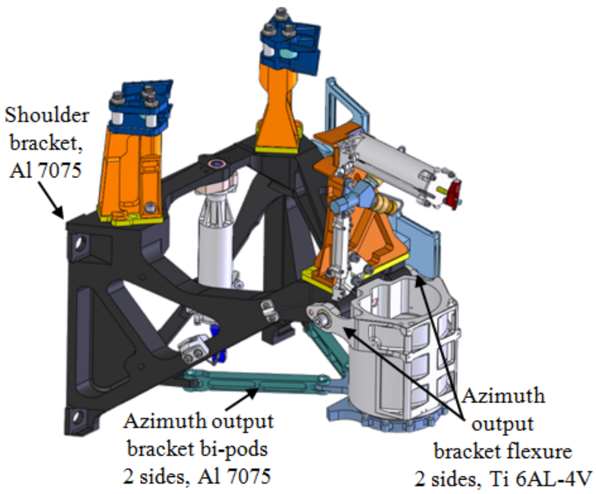


Figure 6, Shoulder bracket and AZ output bracket

The titanium output bracket is designed with integrally-machined flexures which flex with CTE mismatch-induced displacements. Since this part is at the structural root of the RA it was critical that it be designed to be strong enough in all directions to carry the system loads, but comply in the direction of CTE-driven displacements. A bi-pod made of Al 7075 supports the bottom of the titanium coupling piece.

3.4. Actuators

The robotic arm joint actuators were furnished by JPL from a single vendor as were all the actuators on the mission. This was stipulated as a result of the original mission requirement not to use external heaters and use of dry lubrication due to the vendor's experience with dry lubricants. MDA-US typically designs robotic arm actuators in conjunction with the development of the entire arm. Since the MSL RA actuators were designed somewhat independently and supplied to MDA-US, actuator design parameters that would normally be open to adjustment such as output gearing and bearing size were for the most part unchangeable. The robotic arm structure and mechanisms therefore had to serve the dual purpose of accommodating all the design loads while protecting the actuators as delivered. Unlike other robotic arms that MDA-US designed, an additional DOF constraint was added to one of the caging mechanisms because loads were over-stressing the output bearings of the turret actuator. Interestingly, the additional DOF was added to the elbow caging mechanism rather than to the turret caging mechanism, a good demonstration of loads dependency throughout the arm. Another deviation from typical MDA-US practice was that the joint actuator hardstops had to be designed into interface pieces which were then attached to the actuators. This was because actuator range of motion design was MDA-US's responsibility. Obviously this was less efficient and accurate than designing hardstop features directly into the output shaft and housing, not to mention the need for coordination between MDA-US and the actuator manufacturer. Another complication was that because hardstop structures, specifically as part of a robotic arm, take tremendous loads, the parts had to be designed early enough to be match drilled and later pinned to the actuator output shafts before the actuators were assembled. This meant that configurational changes had to be set very early. If changes were needed too long after the match-pinning process, there was a very real risk of having to match-machine on a fully assembled actuator. Despite the precautions taken, because of the aforementioned change in actuator material, much of the match drilling had to be redone following program approval of a fully built and tested actuator made of the new material.

4. TESTING

Elements of the test program fell into two categories: validation and system testing. Validation testing consisted of subsystem tests. Two life tests were conducted, caging mechanisms and flex spool bearing dry lubrication. Static tests were performed on the main structural members. System testing consisted of the full robotic arm assembly for range of motion, vibration, and thermal vacuum tests.

4.1. Life test: Caging mechanism

The turret re-stow life test was composed of two sub-tests which together simulated the two distinct mating geometries and respective tribologies involved in re-stowing the turret. The first sub-test was life-cycling a +X capture "parapet" interface, forward-mounted on the turret re-stow system. The parapets are small structural towers (or pylons) with special features into which corresponding turret features engage. The second was life cycling the –X "hook/duckbill/roller" capture system. The way this caging interface functions is that a hook-shaped piece is guided into the widening "mouth" of the duckbill piece, assisted by a rolling element to limit drag and/or binding friction. Two rear-mounted parapets, similar to the forward mounted parapet, support the duckbill guides and rollers. The geometry simulation hardware for each turret interface test incorporated flexures designed to simulate the stiffness of the turret as mounted at the end of the forearm with the elbow caging mechanism engaged. Both subtests were conducted at ambient temperature and pressure. Each test was 975 cycles (3 times the expected cycles of 325). One cycle is defined as a turret rotation from 50 degrees (start of re-stow and non-contacting) to 0 degrees (full re-stow) and back to 50 degrees. Cycles were conducted at a speed of approximately 1 RPM, which is more than or equal to typical Mars operational stowing speeds.

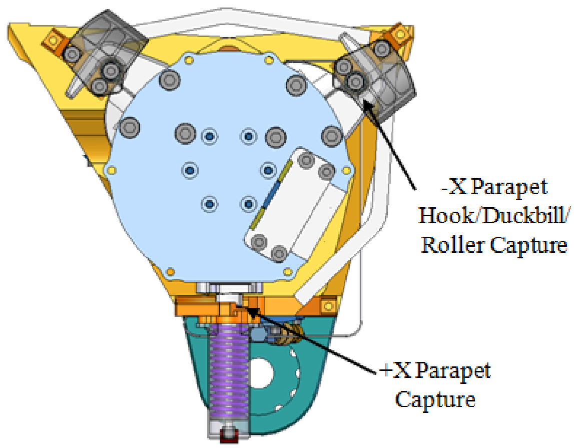


Figure 7, caging mechanism life testing

Under perfect alignment the re-stow capture features will not come into contact with each other and there will be no induced load or wear. This ideal case is obviously not conservative, so both of the aforementioned sub-tests were set up to generate a worst-case misalignment load between the mating pieces. Load values were calculated from worst-case scenarios with the rover at a 30-degree tilt along with the RA joint angles set at allowable imprecision extremes. This resulted in the re-stow capture pieces displaced from each other with a misalignment of +/-8mm.

At +/-8mm, the +X capture feature simulator generated a load that increased during capture up to 342 N at the final stowed location.

Loading on the hook/-duckbill capture interface similarly increased during capture up to a normal load of 418 N. The hook/roller capture interface was subjected to a radial load of 271 N. See Fig. 8 for wear patterns developed.

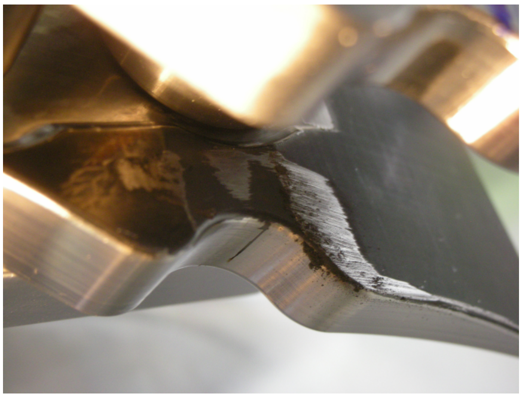


Figure 8, wear pattern on parapet duckbill

Both tests were successful despite all the coatings of Tiodize and MoS2 wearing away before the end of the first lifetime. These coating were applied to titanium 6Al-4V and Nitronic 60 materials, respectively. Nevertheless, the contacting geometry and interfacing features were designed with heavy wear in mind and margins were still maintained by the end of the test.

4.2. Life test: Flex spool bearing dry lubrication

The ball bearing used in the turret and azimuth flex spools is a thin section Kaydon X-type bearing with a thin dense chrome coating and a sputtered MoS2 lubricant. This bearing allows each flex spool to rotate with the joint (the other 3 flex spools were kinematically inverted and thus fixed). The spool bearing life test consisted of 27,000 cycles (3 times the expected 9,000 cycles). A cycle is defined as a positive rotation of 400 degrees followed by a negative rotation of 400 degrees. Testing was conducted at a speed of approximately 10 RPM. Typical Mars operational speeds are less than 1.5 RPM.

Before the life cycling began the bearing was statically loaded to simulate launch loads with an axial load of 378 N applied at the center of bearing and a radial load of 191 N applied through flex spool mid-plane, 37 mm from bearing face. The bearing assembly configured for the life test was designed with an offset load that simulated loading due to the flex cable side loading the spool.

Testing was carried out at several different operational temperature points between -135ºC and +70ºC. Each day the test apparatus was heated to 70ºC to evaporate excess moisture, and then the temperature was ramped to the soak temperature for the test.

4.3. Static testing

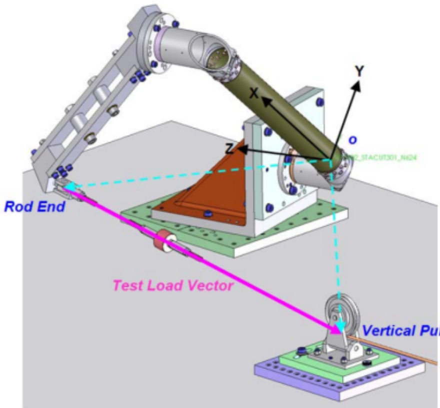


Figure 9, Upper arm MX torsion test, 977 N-m applied

Static tests were conducted on all structural members and subassemblies that could not be verified with analysis no-test factors of safety or system vibration testing. Because the robotic arm operations involve preloading certain instruments on the surface of Mars there are many cases where these preloads are design-driving loads for the structural members. Because of the geometric complexity of these loads with repect to arm pose, it is impossible to generate them during vibration testing. 11 operational loading cases were found where a special static test was needed to simulate them. The upper arm was loaded in 4 different scenarios, and the forearm was loaded in 3 scenarios. The elbow tripod, which is used as a structural base for the restraint and caging mechanism during launch and landing was tested in 2 scenarios, and the shoulder assembly was tested in 2. A typical setup is shown in Fig. 9 using pulleys and winches arranged in a complex configuration with respect to the arm structure to generate the loads, with load cells in-line.

4.4. System Testing: Functional testing, Range of Motion

The first test typically conducted on a fully assembled robotic arm is a functional checkout in conjunction with a full range of motion test. Each joint is driven to both hardstops extreme and the full travel angle is verified to be as designed. During this process there are pre-defined locations along the arm to check for close clearances and to verify that these clearances measure equal to or larger than minimum allowables.

Due to the complexity of motion of a 5-DOF robotic arm completely outfitted with cabling and connectors, it was likely that the first time this test was run there could be areas of close clearance or interference that were not detected in the CAD model. This was the case on the engineering model robotic arm. During motion, a bracket that affixed a portion of the flex cable to the shoulder assembly came to a point of interference while moving to the azimuth hardstop.

4.5. System Testing: Vibration

The objectives of the vibration test were to verify that the RA can survive launch, entry, and landing quasi-static loads and to justify the use of tested factors of safety. Both random vibration and sine vibration tests were conducted in 3 axes. Pre-test and post-test low-level sine-sweeps were conducted to verify that the structure did not change (i.e., loosen or otherwise shift in stiffness) during testing. Post-test visual inspection did not find any anomalies.

4.6. System Testing: Thermal Vacuum

Thermal Vacuum (TVAC) testing was conducted to validate that the RA design was tolerant to the hot and cold temperature requirements of the mission, as well as to characterize the actuators and the effectivity of the actuator heaters. The proto flight non-operational temperature range was -135ºC to +70ºC., and the operational temperature range was were -120ºC to +50ºC. The robotic arm was also exposed to a planetary bakeout temperature of +110ºC. Tests were conducted in the 10 foot diameter chamber at JPL's Environmental Test Laboratories. A large chamber such as this was needed to conduct range of motion testing. Fig. 10 shows the robotic arm during a dry run of the TVAC ROM testing performed outside of the chamber to validate proper motion free of contact with chamber walls or support structure during actual TVAC testing.

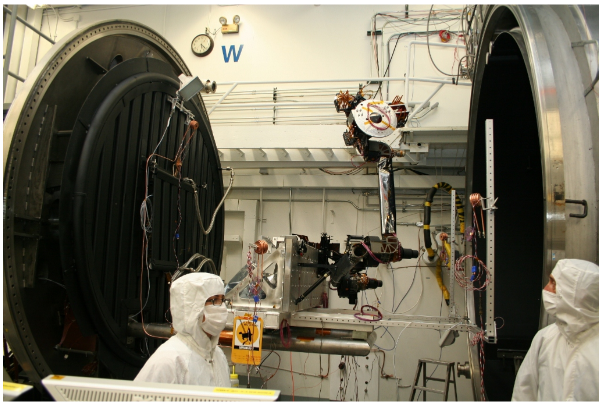


Figure 10, pre-TVAC ROM testing

During the entire test a flex-cable continuity test was performed to ensure that the flex-cable system did not produce any short or open circuits at temperature and vacuum. To visually monitor the functional testing four cameras and lights were placed in the chamber.

Thermal cycling started with an initial ramp to +110ºC bakeoff temperature. To test if the thermal cycling induced damage or altered the robotic arm hardware in any way, three thermal cycles between -135ºC and +70ºC were performed before functional testing commenced. At the end of the third cold cycle at -135ºC, the launch lock caging mechanisms were pyrotechnically released. The caging mechanisms release was visually confirmed by the 4 cameras and proven by commanding first motion of the arm, a smaller subset motion of the aforementioned functional ROM tests. The robotic arm temperature was then raised to the cold protoflight operational temperature of -70ºC. At this temperature a functional ROM was conducted. During the ROM test, the first few actuator moves were successful, but when the elbow actuator was commanded to initialize it did not return telemetry indicating proper behavior. After a few hours of trouble-shooting it was discovered that the electronic ground support equipment (EGSE) was not driving the encoder circuit with sufficient voltage. External power supplies were added to the 3 large actuators which share an identical encoder telemetry circuit and the test continued without any further encoder issues. The robotic arm temperature was then raised to the hot protoflight operational temperature of +70ºC and a complete functional ROM test was conducted. The next phase of the TVAC testing continued with thermal characterization and heater effectivity tests. These tests were used to characterize the time it takes the actuator to heat to operational allowable temperatures from the non-op cold temperature of -120ºC. As each actuator arrived at its operational temperature of -70ºC a ROM test was conducted on that particular joint. This tests the flex cable at that joint at its coldest temperature. During the heater testing, an open circuit was observed on the MAHLI camera flex cable. The chamber was opened for inspection of the robotic arm. After troubleshooting the flex-cable test setup to verify all connections were valid, a time domain reflectometer (TDR) was brought in to try to pinpoint the location of the open circuit on the 10 m long flex cable. The TDR found an open in the area of the elbow flex spool bracket. The flex spool was removed and a damaged flex cable was found. The damage was caused by a small protrusion (~1mm) of material that had been mistakenly left unmachined on the bracket during manufacturing. The temperature of the flex cable at the time of the damage was approximately at -120ºC when the elbow actuator was being moved. At very low temperature such as this, the non-metallic flex cable materials are below glass transition temperature. The damage to the layer of flex-cable had a "shattered" appearance. Other flex cables that lay on top of the MAHLI cable had visible deformation but did not break or cause an open circuit. The MAHLI cable happens to be the thickest of the flex cables because of its matched impedance design, so it is prone to higher bending stresses for a give radius of bend. It was determined that the cables were damaged beyond a flight-acceptable repair and needed to be replaced. The cables were temporarily patched, however, and the TVAC test was scheduled to continue at a later date.

The robotic arm was then delivered to JPL ATLO and integrated onto the rover for system-level testing. During the Fall 2010 MSL scheduled rework cycle, the arm was taken off the rover and the 3 damaged flex cables were replaced. To verify the fix was successful, an abridged set of TVAC ROM tests were performed following installation. This was done to expose the new flex cables to the same conditions and movements that caused the first set of cables to fail and verify the problem had been erradicated. The heater characterization tests were also completed at this time.

5. LESSONS LEARNED

The Mars Science Laboratory is the most ambitious Mars mission to date and encompasses countless subsystems. The main lesson associated with this project is related to the amount of scope change that took place over the course of the design. Efficiently maximizing the design was hindered substantially each time the scope changed. The two substantial scope changes were the more than doubling of the turret instrument mass and tribological issues with the actuators which lead to a substantial actuator mass increase. Both had a large effect on the project progress from design, analysis, and through to manufacturing.

Having the actuators built by an outside source rather than designed concurrently by the arm developer presented additional challenges. As stated previously, a mass and volume-efficient robotic arm must be designed as an integrated system, including its actuators. There were mass and volume inefficiencies due to additional interfaces needed because of this disconnect. The whole MSL mission struggled with this situation of only one manufacturer being responsible for every actuator on the rover.

The importance of mechanical ground support equipment (MGSE) cannot be underestimated when a system is too large to handle by hand. The design, fabrication, and proof-testing of all the necessary MGSE for the robotic arm was a very large task, almost a project unto itself. Another scope change risk was that the assembly and turn-over fixture was not sufficiently sized to adequately support the robotic arm for its full ROM. A complex ROM test had to be choreographed and analysed so that the stress on the assembly fixture would be below its structural limits. This caused issues at time of assembly as well as during testing because many extra motion command steps were needed to manipulate the robotic arm to adhere to load limits. Proof-testing of the MGSE was a large task because of the large amounts of mass and/or force that had to be applied. MSL Program delays also caused many of the proof-test certifications to expire requiring re-proof testing.

Static testing was another large task that was underestimated. Because of the nearly unlimited ways a robotic arm can be oriented, a vibration test cannot validate the structure for all load cases. Complex MGSE for static test had to be designed, analyzed, manufactured, assembled, and proof-tested. This time and effort were not accounted for in the original scope.

The issues encountered with the flex cable in TVAC testing were obviously unexpected. The designers and manufacturing engineers are all very aware of the functionality of the flex-cable brackets and the need for them to be smooth and non-binding to the flex-cables. The problematic bracket, one of hundreds in the assembly, had a manufacturing defect that was not found in inspection. The drawings for the bracket were made using a limited dimensioning scheme which did not directly provide detail of the area of the defect. Because of this, the erroneously protruding feature was not inspected and therefore not detected. Before flex-brackets are completed, the cabling engineer will typically inspect by hand all edges of the bracket that come in contact with the flex cable. The problem was still not detected however because the defect was smooth but protruded just enough to catch the edge of the flex-cables. A procedure to carry out a more detailed inspection of all flex brackets with the CAD model will be implemented in the future.

The caging mechanism life tests provided passing results though with a different outcome than expected. It was known that the contact stress of these parts contacting and rubbing would produce debris and wear the coatings. What was unclear before the test was how much debris would be generated and how much of the actual metal would be worn away. The passing criterion for the mechanism was that the torque required to cycle the caging mechanism be below a specified threshold, approximately a tenth of the actuators stall torque. Studying the torque numbers over the life test revealed that the torque used went up and down fairly cyclical over the course of the life test. It was surmised that the rise of the torque was caused when the two contacting surfaces were directly abrading the metal. When the required torque underwent a downward trend it was surmised that the two contacting surfaces were riding on the abraded debris which acted like ball bearings introducing rolling motion characteristics. As previously discussed, this was a worst-case test with full-load contact derived from worst-case misalignment imposed on every test cycle. Re-stowing the robotic arm under laboratory conditions has demonstrated very little contact of the interfacing caging surfaces and no abrasions to date.

6. CONCLUSIONS

The 4 year project has been a success so far with only a few anomalies on the way. Lessons learned will be used to plan and carry out future projects in a more efficient process. But the project won't be over until the robotic arm has been deployed successfully on the surface of Mars.