Test and Validation of the Mars Science Laboratory Robotic Arm *

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Abstract - *The Mars Science Laboratory Robotic Arm (RA) is a key component for achieving the primary scientific goals of the mission. The RA supports sample acquisition by precisely positioning a scoop above loose regolith or accurately preloading a percussive drill on Martian rocks or rover-mounted organic check materials. It assists sample processing by orienting a sample processing unit called CHIMRA through a series of gravity-relative orientations and sample delivery by positioning the sample portion door above an instrument inlet or the observation tray. In addition the RA facilitates contact science by accurately positioning the dust removal tool, Alpha Particle X-Ray Spectrometer (APXS) and the Mars Hand Lens Imager (MAHLI) relative to surface targets. In order to fulfill these seemingly disparate science objectives the RA must satisfy a variety of accuracy and performance requirements. This paper describes the necessary arm requirement specification and the test campaign to demonstrate these requirements were satisfied.*

Keywords: Manipulation, space robotics, robotic arm.

1 Introduction

The Mars Science Laboratory rover, named Curiosity, is the most advanced robotic explorer ever sent to the Martian surface. Its primary mission is to assess Martian past, present and future habitability. Curiosity investigates Martian habitability by studying the history of Martian geology and climate as recorded in its rocks and soil. To achieve these objectives Curiosity acquires soil samples with its arm-mounted scoop and generates powder samples from rocks with its drill. The rover uses its arm to process and deliver samples to on-board instruments SAM and CheMin for in-situ analysis. In addition the arm positions contact science instruments over surface targets in order to assess the chemistry and mineralogy of soil and rocks. As such the robotic arm is absolutely crucial to achieving mission objectives [1].

A team of scientists and engineers on Earth performs activity planning and command sequence generation in a process similar to the Mars Exploration Rovers (MER) [2]. Sequences are uplinked to the rover each sol, or Martian day, and are executed by onboard flight software (FSW) to perform the planned activity. Upon conclusion of the sol's activity the FSW reports data so engineers can assess rover health and status.

This paper will summarize the system level requirements that drove the design of the robotic arm in Section 2. A brief description of the arm and turret hardware will follow in Section 3. Software behaviors that support the requirements will be described in Section 4. Finally the test and validation campaign will be summarized in Section 5.

2 Driving Requirements

The robotic arm has 4 primary and numerous secondary functional requirements to achieve MSL mission objectives. The primary functions of the robotic arm are as follows:

1. Contact Science: The arm must place turret-mounted instruments and tools relative to surface targets, both rocks and regolith. Stereo cameras mounted on the mast (Navcams) or body-fixed (Hazcams) are used to specify the target 3D coordinates and surface normal relative to the rover. On-board arm FSW drives the selected tool to a pose defined relative to the target.
2. Sample Acquisition: The arm must place and preload the drill on rock targets or position the scoop relative to loose regolith to acquire samples.
3. Sample Processing: The arm must support sample processing. Sample is processed in CHIMRA through sieves using vibration and gravity-relative turret motions generated by the arm.
4. Sample Delivery: The arm must support sample drop-off by positioning the turret relative to on-board instruments, SAM and CheMin, and the observation tray.

Secondary functions include the positioning of turret-mounted instruments and tools relative to rover-mounted

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hardware to perform rover inspection, drill bit exchange, acquisition of organic check material (OCM) samples for instrument calibration, and calibration of APXS and MAHLI.

Essentially the primary function of the RA is to position the turret-mounted instruments and tools with respect to Mars surface or rover-mounted targets. The key requirement levied against absolute positioning accuracy is the arm shall be placed with an accuracy of ≤ 20 mm in position and 10 degrees in orientation relative to the surface normal of a target selected in stereo imagery. Positioning accuracy is to be $\leq$ 15 mm for instruments that can sense contact with the target (lateral accuracy). The arm is required to have a repeatability of ≤ 10 mm.

A key contact science requirement is for the system to be capable of deploying and placing an instrument on a surface target determined from stereo imagery, retracting the instrument and placing another instrument or tool within a single command cycle. All requirements related to contact science are applicable to rover tilts up to 30 degrees.

Arm requirements regarding science target operations are specified with respect to the arm's primary workspace. The workspace is a 1 meter tall vertically oriented cylinder with a radius of 800mm, as shown in Figure 1. It is located 1.1m in front of the rovers front panel and extends 200mm below the level of the rovers front wheels. The system is required to be capable of sample acquisition at 90% of the reachable targets within the primary workspace. In addition the system is required to be capable of acquiring, processing and delivering samples to science instruments when the rover has a tilt up to 20 degrees.

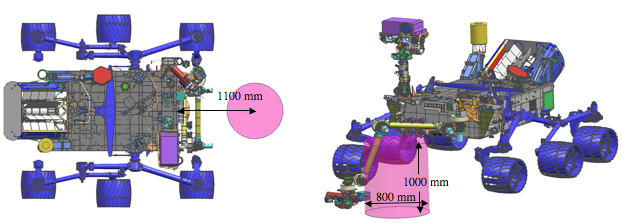

Figure 1: MSL Robotic Arm Primary Workspace

3 Robotic Arm Overview

The MSL robotic arm (RA) is the most complex yet most capable manipulator ever sent to another planetary surface. The robotic arm is a 5 degree-of-freedom manipulator supporting a 30-kg payload mounted at the end of the arm. The turret mounted payload includes two in-situ instruments, MAHLI and APXS, and three tools, the drill, CHIMRA, and a dust removal tool (DRT).

3.1 Robotic Arm Hardware Description

The robotic arm has five joints: shoulder azimuth, shoulder elevation, elbow, wrist, and turret arranged as shown in Figure 2. This kinematic configuration is similar to the MER IDD [3]. The arm and turret together have a mass of approximately 100kg and a reach of over 2 m. This accounts for nearly 10% of the entire mass of the rover. The cabling alone weighs more than either the entire Phoenix robotic arm [4] or MER IDD.

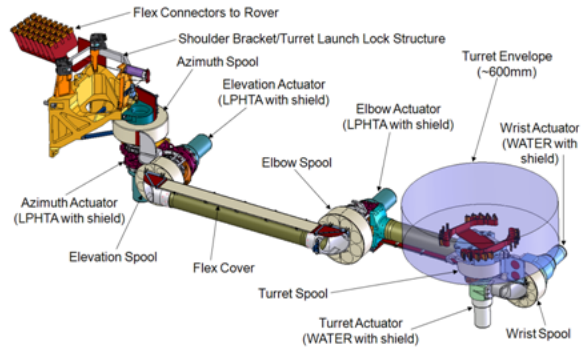

Figure 2: MSL Robotic Arm Layout

Each of the five arm joints is driven by an actuator consisting of a brushless DC motor integrated with an encoder, a planetary gearhead, a resolver, a brake, and hardstop hardware. Motor angular position is measured by the incremental encoder. Actuator output angle (joint angle) is inferred from motor position through the gearhead reduction ratio. The joint angle is also measured directly by the resolver. After joint motions are complete the brakes are engaged to hold the motor position without servoing (and without power). The two shoulder joints and the elbow use Low Power High Torque Actuators (LPHTAs). The remaining joints use Wrist and Turret Actuators (WATERs). A summary of the capabilities of these actuators is shown in Table 1.

Parameter	Units	LPHTA	WATER
Gear Ratio	none	7520	4624
Max Output Torque	Nm	1143	259
Max Current Limit	A	5	3
Max Speed	RPM	0.532	0.865
Backlash	mrad	3.64	4.36
Brake Holding Torque	Nm	1313	517
Mass	kg	7.8	4.24

Table 1: Arm Actuator Basic Operational Specifications

3.2 Turret

The robotic arm boasts the most complete tool suite ever flown on a manipulator. The drill forms the backbone of the turret as shown in Figure 3. The CHIMRA and DRT are mounted directly to the drill housing. The APXS and MAHLI are mounted to the drill via isolators designed to

protect the instruments from the vibration created by drill percussion and CHIMRA vibration.

Briefly, the purpose and function of each of the tools/instruments is as follows.

1. The drill is the primary sample acquisition device. The drill requires an initial preload on its stabilizers of approximately 300N to prevent slipping.
2. CHIMRA is the primary sample processing and delivery mechanism. Sample is either received from the drill or obtained by its scoop. CHIMRA has sieves and chambers designed to sift and portion sample for delivery to the CheMin and SAM instruments.
3. The APXS is a contact instrument that uses X-ray spectroscopy to determine the composition of soil and rocks.
4. MAHLI is a microscopic imager with a z-focus (axial focus) mechanism which allows focus both close-up and at infinity.
5. The Dust Removal Tool (DRT) is a wire brush used to sweep loose material from rock surfaces exposing a fresh surface for contact science observations.

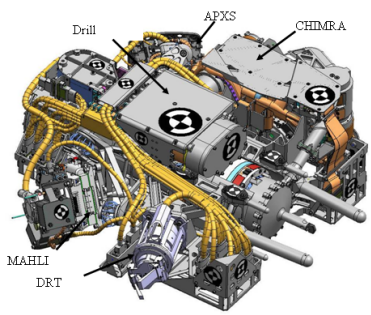

Figure 3: Robotic Arm Turret

The APXS, MAHLI and DRILL are equipped with redundant limit switches to detect contact between the instrument or tool and a target surface. The APXS and MAHLI CSWs are similar to the MER MossBauer Contact Plate and microscopic imager contact sensor designs, respectively [3]. The APXS contact sensor is implemented as a contact plate. The MAHLI contact sensor is a double poker system each with two redundant limit switches. Both the APXS and MAHLI contact switches register contact (switches close) with a force of approximately 3 N. The drill CSW detects surface contact and stabilizes the arm during drilling. The sensor consists of two coupled stabilizer prongs designed to accommodate approximately 15 degrees of misalignment with the target surface normal. Both stabilizer prongs have to contact the surface before either switch will close. The switches close at approximately 20-30 N.

4 Robotic Arm Motion Behaviors

Control of the arm is achieved through a distributed architecture. At the highest level is the arm FSW resident on the Rover Compute Element (RCE). It receives commands from the sequence engine and generates high level and low level arm motion behaviors designed to achieve the functional requirements of the system. At the lowest level is the Motor Control Flight Software (MCFSW) running on the SPARC processors in the Rover Motor Control Assembly (RMCA). The MCFSW provides PID control and low level motion fault protection and operates at a 512 Hz control rate.

4.1 Arm Low Level Behaviors

Low level arm behaviors consist of single arm motions and include forward/inverse kinematics, trajectory generation, position compensation, drill stabilizer preloading, fault monitoring and response. Low level motion behaviors may be commanded in joint or Cartesian space. In Joint Space motion, one or more of the five arm joints is moved to a specified goal. Cartesian motion moves a specified turret feature, usually a tool tip, to a specified position (x,y,z) and orientation (azimuth and elevation angle) in space. The motions of all five joints are coordinated such that the feature travels a straight-line path from the starting position to the ending position. The resulting trajectory consists of a series of intermediate goals or via points. After a trajectory is computed, RA motion is executed by sending requests to the MOT FSW module and monitoring the actuator state data returned by MOT FSW. In turn MOT interfaces to the MCFSW. Arm moves may be executed in any of five unique modes as described in Table 2.

Table 2: Motion Modes

Mode	Description
Free-space	No contact expected during motion.
Guarded	Motion ends nominally when contact is detected by the active tool CSW or when the move completes without contact detected. If the tool is the drill, motion ends nominally only when the drill CSW triggers. Final pose is saved for future use as a target.
Preload	Active tool expected to remain in contact throughout motion.
Retracting	Active tool CSW expected to change to not-in-contact state during removal of tool from surface contact.
Vibe	Ignore all CSWs during motion.

The robotic arm FSW compensates for several sources of tool positioning error. As previously mentioned the arm has a long reach (> 2 m) and a heavy turret (> 30 kg). Using the nominal (rigid) forward/inverse kinematics to position the arm would result in a positioning error of several centimeters due to deflection of the turret under gravity. This positioning error is pose dependent, i.e. the error grows as the target moves farther from the base of the arm. The deflection is dependent on rover tilt as well because it affects the orientation of the arm with respect to gravity. The arm

FSW uses an on-board mass/stiffness model of the arm to compute the deflected arm pose. The commanded pose is adjusted using this computed deflection. The model compensates for temperature-based deflection and joint backlash as well.

Preloading of the drill stabilizers is achieved by overdriving the arm joints after contact is detected. The FSW computes the overdrive distance using the aforementioned mass/stiffness model.

FSW fault protection (FP) consists of both pre-motion checks and motion fault monitors. Prior to initiating motion, the arm FSW performs checks to verify that it is safe to proceed. These includes trajectory validation and checking each via point for potential collisions between the RA and rover objects. During motion the FSW monitors the state of the motors and CSWs and checks that thermal and force/torque (F/T) sensor data are within acceptable bounds.

4.2 High Level Behaviors

High level behaviors expand into low level behaviors for ease of sequencing. An example behavior is ARM_UNSTOW which unstows the arm using a series of single joint moves. Additional high level behaviors facilitate contact science and sample processing.

The arm has two high level behaviors to facilitate contact science planning.

The ARM_PLACE_TOOL behavior creates a sequence of moves to place the specified tool at the current target. The current target is defined as a point (x, y, z) and approach vector (azimuth, elevation) using stereo imagery.

The ARM_CHANGE_TOOL behavior performs a sequence of moves to retract the current tool from contact with the target and places a new tool on the target.

Sample processing and delivery requires that the arm orient the turret in a number of poses relative to gravity. The arm FSW has a set of gravity relative behaviors to achieve this objective. These behaviors are outlined in Table 3.

Table 3: Gravity Relative Behaviors

point_grav	Aligns a turret vector with gravity using wrist/turret only.
move_constant_grav	Move a tool to the (x,y,z) goal while maintaining the turret aligned with gravity.
move_grav_joint	Move the shoulder and elbow joints to the specified goal while maintaining the turret aligned with gravity.
move_grav	Move a tool to the (x,y,z) goal and point a turret vector along gravity.
move_to_process	Move the arm to the processing pose after acquiring sample for transferring to CHIMRA while maintaining the turret aligned with gravity during the move.
move_to_deck_ready	Move the turret to the deck-ready pose while maintaining the turret aligned with gravity. The deck-ready pose is a starting point for CHIMRA sampling activities over the deck including portion generation and sample drop-off.

5 Test Campaign

The primary goal of the arm test campaign was to verify that arm system requirements were met satisfactorily. This process included the determination and fine tuning of parameters that govern arm FSW behaviors and the collection of ground truth data to validate calibration results. The test campaign began with initial checks of the integrated flight system during the basic functional and proceeded with tests designed to calibrate and assess arm performance.

5.1 Arm Basic Functional Test

The arm basic functional was the initial checkout of the full flight system including the mechanical hardware, avionics and FSW. The basic functional consisted of both single joint and multi-joint motion. Single-joint move tests were designed to verify correct actuator phasing, controller parameter values, move types and range of motion (RoM) checks for each of the five Arm actuators. Hard-stop calibration was performed for each of the five joints. Multi-joint move tests checked out coordinated joint space and cartesian motion capability. Data was collected for the resolvers, encoders, PRTs and F/T sensors and ground data telemetry was validated.

5.2 Arm Calibration and Positioning Performance Test

The robotic arm calibration test involved the collection of arm state data and turret position truth data for arm kinematic and stiffness parameter calibration. The calibration data set consisted of 160 arm poses selected throughout the primary workspace. Data was collected with two different turret mass configurations and two different tilts (0 degrees and 20 degree roll) to excerise the arm stiffness model boundary conditions and enrich the calibration data set. Ground truth data was generated using laser metrology. The calibration data set was processed to generate the kinematic and stiffness model parameters used by the arm FSW. Additional data sets were collected to provide independent assessments of arm free-space absolute accuracy and repeatability. For additional details see [5].

5.3 Arm Placement and Preload Performance Functional Test

The purpose of the arm placement and preload performance functional was to assess the ability of the arm to accurately place the APXS or MAHLI or place and preload the

drill stabilizers on surface targets. This test employed the full mass turret and the calibrated kinematic and stiffness parameters. The test began by verifying arm motion mode behavior as outlined in Table 2. After verifying motion mode behavior a number of placement and preload exercises were performed. A reconfigurable target fixture was used to provide multiple surface target positions and orientations. The target included a 6-axis force/torque sensor to provide ground truth during drill preloading. Laser metrology was employed to provide coordinates of the target fixture for arm placement commands as well as to generate turret position truth data. Tests were performed both with the rover flat and rolled 20 degrees.

5.4 Arm Teach Point Functional Test

Teach points are arm poses that position turret-mounted hardware in close proximity to critical rover hardware to perform certain activities. The full set of critical teach point hardware is shown in Figure 4. Operations involving teach points include arm stow/unstow, sample drop-off to the science instruments and observation tray, drill bit exchange, OCM sample acquisition, docking with the portioner pokers, and positioning of the APXS and MAHLI at their respective calibration targets.

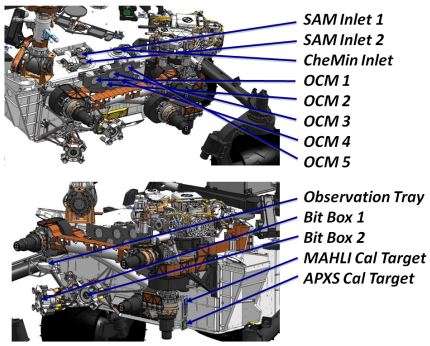

Figure 4: Arm Teach Point Hardware.

Arm teach points operate on the principle that arm repeatability is significantly better than absolute arm accuracy. Teach points were generated prior to launch using the following process. First, teach point targets were measured with metrology. Next the relevant tool was positioned at the nominal pose with respect to the teach point target. Then metrology was used to fine tune the arm pose. Finally the dialed-in arm pose was recorded as the teach point.

5.5 Arm End-to-End Accuracy Test

Robotic arm end-to-end positioning accuracy deals with how accurately the arm can be placed on a target generated by stereo imagery. End-to-end accuracy can be divided into image-based targeting and absolute arm positioning accuracy. Image-based targeting accuracy consists of how well an operator can select a desired target in an image as well as how accurately the camera model can generate a 3D target via stereo correlation and triangulation. Factors affecting targeting accuracy include camera resolution, target range, and whether the cameras are body-fixed or mast-mounted. Arm positioning accuracy constitutes the other half of end-to-end positioning accuracy. The arm calibration process was summarized in Section 5.2. Arm positioning accuracy is affected by arm kinematic model knowledge (link lengths and joint offsets), arm mass and stiffness model accuracy including backlash compensation, and joint level controller resolution (controller deadbands and servo resolution).

It was not possible to test the end-to-end positioning capability of the flight vehicle with natural targets due to the requirement to keep the vehicle pristine prior to landing on Mars. Instead the vehicle system testbed (VSTB), a near clone of the flight vehicle, served as a surrogate. Targets were placed throughout the robotic arm workspace. Fiducials were fixed to each target to minimize target designation error which can be highly user dependent. Targets were imaged with both the Navcams and Hazcams and stereo data was generated. Targets were designated by selecting the center of the Fiducial in both Navcam and Hazcam images. Once the targets were designated, arm motions were planned to place various tools relative to the targets (both above and in contact). Metrology was used to ground truth the target positions as well as the turret pose at each target in order to assess various error sources. For additional details see [6].

5.6 Integrated Sample Chain Tests (ISC)

ISC tests demonstrated the ability to acquire samples, process and deliver portions to science instruments using the flight system. These tests were performed on the VSTB in a sandbox. Additional test programs involve thermal vacuum chambers to simulate Martian pressure and temperature, however that work is outside the scope of this paper.

6 Flight Sequence Test and Validation

The VSTB is used to test and validate sequences prior to execution on the flight vehicle. A prime example is the MAHLI rover self-portrait. First the robotic arm engineers planned the self-portrait using Rover Sequencing and Visualization Program (RSVP) [7]. Motion was generated by holding the focal point fixed throughout the activity and rotating the MAHLI boresight to image the whole rover as demonstrated in Figure 5. Approximately 60 MAHLI images were acquired to cover the entire rover and nearby terrain. The sequence was tested and refined on the VSTB prior to execution on the rover.

Combining the images into a mosaic produced by far the most outstanding self-portrait of a rover or lander ever acquired during interplanetary robotic exploration and has become the iconic image of Curiosity. Building upon this

capability we can generate a stereo view of the rover as it would be seen by a human observer standing in front of the rover on Mars. A human eye stereo mosaic is achieved by offseting the focal point by the average stereo baseline of adult human eyes (approximately 7 cm) and acquiring a second self-portrait. Stereo is achieved by combining the first mosaic (right eye) with the second mosaic (left eye).

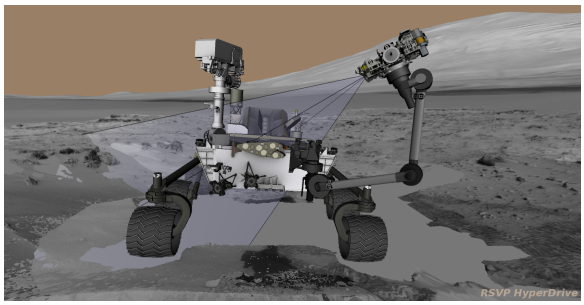

Figure 5: Planning of rover self-portrait in RSVP.

Although the beautiful rover self-portrait can be justified by its public outreach value alone it serves a couple more utilitarian functions. A primary function of the self-portrait is to inspect portions of the rover not visible to the mast-mounted cameras. A secondary function is to document the current state of the vehicle and local terrain in a single image mosaic. The first self-portrait was acquired on sols 84 (right eye) and 85 (right eye). This portrait captures the results of the Rocknest scooping campaign as seen in Figure 6.

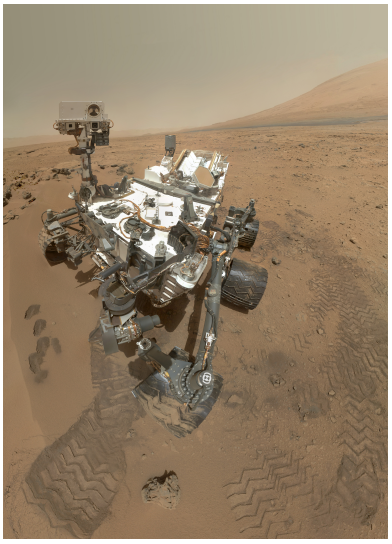

Figure 6: Self-portrait. (Credit: NASA/JPL-Caltech/MSSS)

7 Conclusions

The MSL robotic arm and accompanying turret-mounted hardware is the most complex, yet most capable manipulation system ever flown to another planet. The comprehensive test campaign outlined in this paper verified system level requirements were met and provided strong reassurances that MSL operations objectives could be achieved. Arm performance on the surface has only reinforced this assertion.

8 Acknowledgements

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