In-situ Operations and Planning for the Mars Science Laboratory Robotic Arm: The First 200 Sols

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Abstract - The Robotic Arm (RA) has operated for more than 200 Martian solar days (or sols) since the Mars Science Laboratory rover touched down in Gale Crater on August 5, 2012. During the first seven months on Mars the robotic arm has performed multiple contact science sols including the positioning of the Alpha Particle X-Ray Spectrometer (APXS) and/or Mars Hand Lens Imager (MAHLI) with respect to rocks or loose regolith targets. The RA has supported sample acquisition using both the scoop and drill, sample processing with CHIMRA (Collection and Handling for In-Situ Martian Rock Analysis), and delivery of sample portions to the observation tray, and the SAM (Sample Analysis at Mars) and CHEMIN (Chemistry and Mineralogy) science instruments. This paper describes the planning and execution of robotic arm activities during surface operations, and reviews robotic arm performance results from Mars to date.

Keywords: Manipulation, Mars surface operations, in-situ operations, 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 habitability, past, present and future. 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 analysis. In addition the arm positions contact science instruments over surface targets in order to interrogate 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 is responsible for activity planning, command sequence generation and validation, and rover health and performance monitoring in order to achieve the mission objectives. This paper describes the robotic arm portion of this effort during the first 200 sols on Mars and is outlined as follows: Section 2 presents a brief overview of the robotic arm and turret-mounted hardware. Section 3 describes the initial deployment and check-out of the arm during the Characterization Activity Phase (CAP), the first 30+ sols. Nominal surface operations began at the conclusion of CAP. The rest of the paper summarizes arm activities during this phase of the mission. Section 4 describes the planning, sequencing and validation of arm activities. Sections 5 and 6 describe arm contact science and sampling operations, respectively.

2 Robotic Arm (RA) Overview

The MSL robotic arm is the most complex yet most capable manipulator ever sent to another planetary surface. The RA is a 2.5 meter long, 5 degrees-of-freedom manipulator with a kinematic configuration similar to the MER Instrument Deployment Device (IDD) [2] and boasts the most complete tool suite on a manipulator ever flown.

The robotic arm has two main functions. First the arm enables sample acquisition, processing and delivery. The primary sample acquisition device is the percussive drill. The robotic arm is responsible for the accurate placement and preload of the drill against rock targets. The drill forms the backbone of the turret as shown in Figure 1. The CHIMRA sample processing unit is attached to the drill. Sample is transferred from the drill to CHIMRA by moving the turret through a series of gravity relative motions generated by the arm and motivating the sample via percussion induced vibration. After transfer to CHIMRA the sample is sieved and portioned using additional robotic arm motions and sample motivation with CHIMRA’s vibration mechanism. CHIMRA contains a scoop for acquiring loose regolith material as well. The robotic arm is responsible for the accurate placement of the scoop relative to loose regolith. Sample is delivered to either SAM or CHEMIN for in-situ processing and analysis via CHIMRA’s portion door or the scoop.
### 3 Characterization Activity Phase

The Characterization Activity Phase (CAP) was a series of activities performed at the beginning of the surface mission to checkout the vehicle prior to nominal surface operations. The activities were scripted and tested prior to landing on the vehicle system testbed (VSTB), a near clone of the flight rover. The primary goals of CAP were to verify initial health and safety of the rover post landing and to characterize the rover performance in the Martian environment (temperature, pressure and gravity). A summary of arm activities during the Characterization Phase is presented in Table 1.

Arm activities during CAP were planned with a crawl-walk-run philosophy, i.e. CAP started slowly with simple activities and increased in complexity and pace as operators gained confidence in the vehicle’s performance. The Characterization Phase was divided into CAP 1 and 2. CAP 1 comprised mainly of initial deployment. This included the firing of pyros to release the robotic arm, the setting and verification of arm parameters and initial arm deployment.

A Navcam 3x1 mosaic was acquired of the robotic arm post initial deployment on sol 14 as seen in Figure 2(a).

CAP 2 kicked off on sol 30 after a brief intermission during which the rover was driven from the initial landing zone. CAP 2 activities were designed to assess arm performance as a prerequisite to contact science and sample acquisition and processing operations. The first arm CAP 2 activity involved the characterization of the arm actuators and force/torque (F/T) sensors in the Martian environment. Next the arm was positioned at a series of teach points. The arm position at each teach point was documented with MAHLI and/or Navcam images which were compared to images acquired prior to launch. Teach points are arm poses that position turret-mounted hardware in close proximity to critical rover hardware to assure the safe performance of activities such as sample drop-off, bit exchange, and OCM sample acquisition. The full set of critical teach point hardware is shown in Figure 2(b). Teach point checkout was separated into two rounds with ground in the loop between the rounds. The second round of teach points involved tighter clearances than the first. Teach points included the activation of the MAHLI and APXS contact switches (CSWs) against rover hardware, the calibration target for the APXS and the O-tray for MAHLI, as a prerequisite to contact science activities.

CAP concluded with preloading the drill stabilizers against the OCM bracket as documented in Figure 2(c). The stabilizers were left preloaded on the OCM bracket overnight and the arm F/T sensors were monitored periodically to measure the impact of thermal expansion on arm preload over a diurnal cycle. Using this data we were able to partially assess the arm stiffness model prior to preloading the drill stabilizers on ground targets. Preloading against the rover provided two main advantages. First we were able to simplify the initial checkout by eliminating the effects of rover mobility stiffness. The second advantage was safety. Preloading against a rover mounted target versus ground targets eliminated the danger of rover wheel slip.

### 4 Robotic Arm Operations Planning and Sequencing

Robotic Arm command sequence generation is arguably the most complicated activity during MSL Surface Operations. Complexity is derived from the number of commands and the tightly coordinated interoperability of the arm, turret-mounted mechanisms, rover mounted instruments and mechanisms and the terrain. A command sequence is a series of
flight software (FSW) commands that perform an operation when executed by the rover onboard sequence engine. MSL command sequences are event driven. This means that the next command executes upon receipt of command completion status from the current command. The responsibility for creating and validating robotic arm sequences falls upon the robotic arm rover planners.

Many arm activities such as contact science are sequenced during the tactical timeline however, not all arm operations can be sequenced tactically due to activity complexity. Sample acquisition, processing and delivery sequences are developed strategically for the most part. Complexity is derived from both the number of commands and the tightly coordinated interoperability of the arm, turret-mounted mechanisms and rover mounted instruments and mechanisms. Only those activities that cannot be developed strategically are sequenced during the tactical timeline. For example arm commands to place the drill on a surface target are created tactically because the target may not be finalized prior to the planning sol.

The tactical planning day kicks off with the Target and Activity Coordination Tagup (TACT). This meeting affords an opportunity for the rover planners to discuss potential activities with participating scientists and triage candidate contact science targets. After the TACT the various science working groups develop plan fragments using the Mars Science Laboratory Interface (MSLICE) planning tool. A plan fragment consists of a set of science and engineering activities. These plan fragments are combined into the Sol’s Tactical Activity Plan (TAP) during the Science Operations Working Group (SOWG). MSLICE is used to predict resource usage for the TAP including activity duration, data volume, power usage, and rover battery state of charge. Rover planners can begin to develop the sequence(s) for the sol’s activities during the SOWG. The plan is finalized and approved during the Activity Plan Approval Meeting (APAM). After the APAM the rover planners are responsible for finalizing, reviewing and delivering the sequence. The rover planners verify the sequence(s) complies with associated flight rules governing operation of the rover.

Robotic Arm sequences are developed, validated and delivered using Rover Sequencing and Visualization Program (RSVP) [4]. RSVP has been used for robot arm sequencing on the Phoenix and MER missions in addition to MSL. Sequences are created using RSVP’s sequence editor, often with the aid of programmed macros. An arm macro is a series of commands that are used frequently during arm sequencing with relatively minor changes to command arguments or control structure. Arguments to the macro allow the tailoring of the command expansion for the particular instantiation. RSVP provides simulation of the command sequence(s) using the same flight software running on the rover. This provides high fidelity validation of the command sequence implementation including checks for certain faults such as collisions or trajectory generation errors, as well as an accurate estimation of sequence duration. As its name implies RSVP provides visualization of the sequence execution. This allows the rover planner to check planned arm motions visually including terrain clearances during contact operations. RSVP facilitates the selection of arm targets from imaging panoramas as well.

5 Contact Science

Contact science is defined as the placement of instruments or tools in close proximity to surface targets. The robotic arm has three contact science instruments or tools, the microscopic imager (MAHLI), the Alpha Particle X-Ray Spectrometer (APXS) and the dust removal tool (DRT).

The APXS and MAHLI 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 [2]. The APXS contact sensor is implemented as a contact plate. The redundant switches close after the plate deflects approx-
imately 2-3 mm. The MAHLI contact sensor is a double poker system each with two redundant limit switches. Each poker senses contact after it deflects approximately 2-3 mm along the poker axis. Both the APXS and MAHLI contact switches register contact (switches close) with a force of approximately 3 N. The DRT has no contact switch.

The first contact science activity was performed on sol 46 on target Jake Matijevic. More than 40 of the first 200 soils included some contact science activity. Selected contact science activities are shown in Figure 3.

5.1 APXS Placement

The APXS is a contact instrument that uses X-ray spectroscopy to determine the elemental composition of soil and rocks. The APXS exposes the surface target to alpha particles and X-rays emitted by a radioactive source. The alpha particles and X-rays interact with electrons in the surface, releasing X-rays that can be measured by a detector on the instrument. The APXS source is centered on the opening in the contact plate and is recessed approximately 1.5-2 cm above the undeflected plate. The source has no cover so it is permanently exposed to the environment. Ideally the APXS is placed as close to contact with the surface target as possible. It can be placed safely on most rock surfaces as long as the local surface roughness is reasonably small. There is a slight possibility the APXS CSW would not register contact on very low density soils. This could result in the source being buried in the soil. While this poses no threat to the arm it could result in permanent damage to the sensor. As such APXS contact science on soils is sequenced conservatively to essentially guarantee zero contact with all but very compact soils.

5.2 MAHLI Placement

MAHLI is a microscopic imager with a z-focus (axial focus) mechanism which allows focus both close-up and at infinity. MAHLI images of surface targets are acquired typically at three offset distances from a surface target, a context image at 20-25 cm, a stereo pair at 5-10 cm, and a high resolution image from approximately 1 cm. MAHLI offset distances are referenced with respect to the MAHLI tool frame located along the camera boresight near the midpoint of the two CSWs.

A MAHLI image can be acquired using autofocus. As a side benefit of auto-focus, the focus step can be used to estimate the distance to the target, referred to as range finding. Experiments have shown range finding has an accuracy of within ± 2mm for target distances ≤ 10 cm. This is particularly useful for targets that are not safe to “find” using either the APXS or MAHLI CSWs such as soft soils. Currently the range is estimated manually but there are plans to automate range finding.

Alternatively MAHLI has the capability to acquire z-stacks which consist of a series of images taken from the same pose but with different focus positions. Z-stacks produce coherent focus for targets with unknown surface relief and is particularly effective at close distances.

MAHLI image sequencing is aided by having an accurate estimate of the range to target. The standard approach is to “find” the surface using the APXS CSW to sense contact, retract from the surface, and position MAHLI relative to the contact pose. This provides accurate positioning of MAHLI within a few mm of the desired offset.

5.3 DRT Placement

The Dust Removal Tool (DRT) is a wire brush used to sweep dust and loose material from a rock surface exposing a fresh surface for APXS observations. Brushing is effective at stand-off distances of ≤ 2cm. The arm is used to position the DRT above the surface. The mechanism can be damaged if its center post contacts the surface. Since DRT has no contact switch, the standard approach is to use APXS to accurately “find” the surface, retract from the surface, and position DRT 1 cm above the surface. Brushing is performed by sweeping the DRT across the surface using small rotations of the turret actuator. The results from the Sol 150 brushing are shown in Figure 4(a).

6 Sample Acquisition, Processing and Delivery

Samples are acquired using either the scoop or powdering drill. After acquisition samples are processed using Chimra and delivered to SAM, CHEMIN or the observation tray. A total of 6 samples were acquired during the first 200 sols, 5 with the scoop and 1 with the drill. From these samples 7 portions were delivered to SAM, 4 to CHEMIN and 8 to the Observation Tray.

6.1 Scooping

The arm is responsible for positioning the scoop to acquire a sample. Since the scoop acquires samples from loose regolith we cannot rely on either the MAHLI or APXS CSWs to locate the surface. Rather MAHLI range finding is employed to improve upon arm absolute positioning accuracy when positioning the scoop relative to the surface. Scooping is performed as follows. The arm positions the scoop approximately 10 cm above the surface and the scoop is opened. Next the arm lowers the scoop closer to the surface and the scoop is closed to acquire sample. Finally the arm retracts the scoop from the surface. The scooping results from sol 61 are shown in Figure 4(b).
6.2 Drill Placement and Preload

The robotic arm is responsible for the accurate placement and preload of the drill against rock targets. The arm places the drill stabilizers on a surface using a guarded move. 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 a design load of approximately 20-30 N. After contact is detected the arm provides preload by overdriving the arm joints. The commanded preload for drilling is 300N for drilling operations. The FSW computes the overdrive distance using an on-board stiffness model. This was achieved by comparing the commanded preload to the preload measured by the arm F/T sensor. The stiffness model is pose/configuration dependent so four targets were chosen throughout the arm workspace. A second objective was to validate the thermal component of the stiffness model by measuring the change in preload over a diurnal cycle. Although the nominal plan is to preload, drill and unload in a single sol a fault may occur leaving the arm preloaded on a target overnight. This test aimed to minimize concerns the arm preload could change dramatically over the diurnal cycle, thus risking hardware damage. The objective was achieved by leaving the arm preloaded on the fourth surface target for at least 1 full Martian day (24 hours 40 minutes). The arm F/T sensors were monitored periodically throughout the night. The overnight preload pose is shown in Figure 3(d). A preload of 200N was commanded for each pose in order to provide additional safety margin during this initial checkout.

Mahli images were acquired above each preload target before and after the test. The objective was to locate impressions in the terrain left by the knurled tips of the drill stabilizers. Using this information arm system engineers were able to assess arm placement accuracy by comparing the actual pose to the RSVP predicted pose as shown in Figure 5.

6.2.1 Drill Preload Test

Prior to the first drilling activity on Mars an in-situ preload test was performed on sols 170-171 to assess the ability to preload the drill safely on a surface target in the Martian environment. CAP assessed the ability of the arm to apply preload accurately on a rover target. The sol 170-171 preload test extended the assessment to include the stiffness of the rover mobility system. The test had two main objectives. The first objective was to assess the arm and mobility stiffness model. This was achieved by comparing the commanded preload to the preload measured by the arm F/T sensor. The stiffness model is pose/configuration dependent so four targets were chosen throughout the arm workspace. A second objective was to validate the thermal component of the stiffness model by measuring the change in preload over a diurnal cycle. Although the nominal plan is to preload, drill and unload in a single sol a fault may occur leaving the arm preloaded on a target overnight. This test aimed to minimize concerns the arm preload could change dramatically over the diurnal cycle, thus risking hardware damage. The objective was achieved by leaving the arm preloaded on the fourth surface target for at least 1 full Martian day (24 hours 40 minutes). The arm F/T sensors were monitored periodically throughout the night. The overnight preload pose is shown in Figure 3(d). A preload of 200N was commanded for each pose in order to provide additional safety margin during this initial checkout.

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Figure 5: The arm was placed within approximately 1-1.5 cm of the target on sol 170 (Credit: NASA/JPL-Caltech/MSSS).
6.2.2 Drill Targeting

The first hole ever drilled robotically on another planetary body was performed on Sol 180 (mini-drill hole). A second, deeper hole was drilled on Sol 182 (full drill hole). Both targets were within a few cm of the sol 170-171 overnight preload pose. This allowed arm operators to place the drill at the selected targets with significantly increased accuracy. As aforementioned arm engineers were able to locate the impressions left by the drill stabilizer in the post-retraction MAHLI image. Targets were selected for the mini-hole and full drill hole in the same MAHLI image. Next arm operators located the drill’s reference frame at the overnight preload pose in the image. The target coordinates were converted from MAHLI image frame to drill tool frame using an affine transformation and the camera’s spatial resolution at the distance the image was acquired. The drill was positioned at each target as follows: The drill was positioned a few cm above the overnight preload surface target. Next the arm was commanded with respect to the drill tool frame target coordinate. This positioned the drill above the desired target. Finally the drill was moved to contact the surface and preloaded to 300 N. This process is displayed in Figure 6.

![Figure 6: Selection of drill targets using a MAHLI image from Sol 170-171 (Credit: NASA/JPL-Caltech/MSSS).](image)

The results of the Sol 180 hole (mini-hole) are shown in Figure 7. The center of the hole was estimated to be within approximately 2-3 mm of the target selected in the MAHLI image.

6.3 Sample Processing

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 [3].

7 Conclusions

This paper described the planning and execution of robotic arm activities during the first 200 sols on Mars. Robotic arm activities were planned on approximately 50% of the first 200 sols. These activities included the accurate placement of contact science instruments, the acquisition of regolith with the scoop, the placement and preload of the drill, and the processing and delivery of samples to science instruments using CHIMRA. As such the robotic arm is an absolutely crucial element of the Mars Science Laboratory surface mission. The RA has performed very well over the first 200 sols.

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References


