Robotic Arm In-Situ Operations for the Mars Exploration Rovers Surface Mission

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Abstract - This paper describes the operations of a 5 degree-of-freedom Instrument Deployment Device (IDD), a dexterous robotic manipulator on the Mars Exploration Rovers, Spirit and Opportunity. The unprecedented flawless operations of the IDD enabled precise and reliable placement of at least 3 in situ instruments in sequential order on designated target position on a rock/soil on the Martian surface any time during the Martian diurnal cycle (day or night). These placements demonstrated a repeatability of ~1mm in position and ~1 degree in orientation. This operations breakthrough is the secret hero that enabled the scientist to characterize a wide range of rocks and soils in a timely manner in the hunt for geological clues that revealed that the planet was once rich in water. In this paper we describe the IDD planning and command sequence generation process used to place and hold in situ instruments directly against rock and soil targets of interest within the IDD work volume.

Keywords: Manipulation, In Situ Robotics, Command Sequencing, Mars Exploration, Surface Operations, Planetary Robotics.

1   Introduction

NASA's twin robot geologists, Spirit and Opportunity have slowly and steadily unraveled the geologic story recorded in the Martian rocks and soil at the landing sites. Their findings have provided the long-sought evidence for prolonged surface waters on Mars and put an end to the water debate. The Mars Exploration Rover mission is part of NASA's Mars Exploration Program, a long-term effort of robotic exploration of the red planet. Primary among the mission's scientific goals is to search for and characterize a wide range of rocks and soils that hold clues to past water activity on Mars.

Like the geologists they are meant to mimic, Spirit and Opportunity are equipped with a 5 degree-of-freedom Instrument Deployment Device (IDD), a dexterous robotic manipulator. At the end-effector of the IDD is mounted a unique in situ instrument suite called the Athena science payload [1], that has been designed to measure and understand the detailed geochemistry and morphology of

the surface of Mars. The in situ instrument suite includes a Mössbauer Spectrometer (MB) [2], an Alpha Particle X-ray Spectrometer (APXS) [3], a Microscopic Imager (MI) [4], and a Rock Abrasion Tool (RAT) [5]. The IDD provides a dexterous in situ manipulation capability to enable the placement and holding of the in situ instruments directly against rock and soil targets of interest within the IDD work volume. Thus allowing for detailed inspection of rocks and soil to reveal their elemental and mineralogical composition and document their geological time history of water. Earth-based science and engineering teams perform remote planning, command-sequencing, and command verification to conduct on-site geological investigations with the rovers. Although, few realize it field geology and robotics are both iterative processes of scientific/engineering hypothesis formulation and testing, conducted in a field setting thus they both share a common process. However, performing field geology on a distant planet with a robotic vehicle is an extremely difficult engineering challenge. Unique challenges include limited mobility, power, data bandwidth, soil/rock in situ manipulation capability, navigation errors, and long response time.

The unprecedented flawless operations of the IDD enabled precise and reliable placement of at least 3 in situ instruments in sequential order on designated target position on a rock/soil on the Martian surface any time during the Martian diurnal cycle (day or night). This enabled the scientist to perform coupled observation using the MI, MB, and APXS. These placements demonstrated a repeatability of ~1mm in position and ~1 degree in orientation. The aforementioned IDD operations breakthrough is the secret hero that enabled the scientist to characterize a wide range of rocks and soils in a timely manner in the hunt for geological clues that revealed that the planet was once rich in water.

The sections of this paper that follow are organized as follows: Section 2 presents a brief description of the IDD hardware and control system. Section 3 presents a detailed description of the IDD command sequence generation, results from Spirit and Opportunity rovers during the

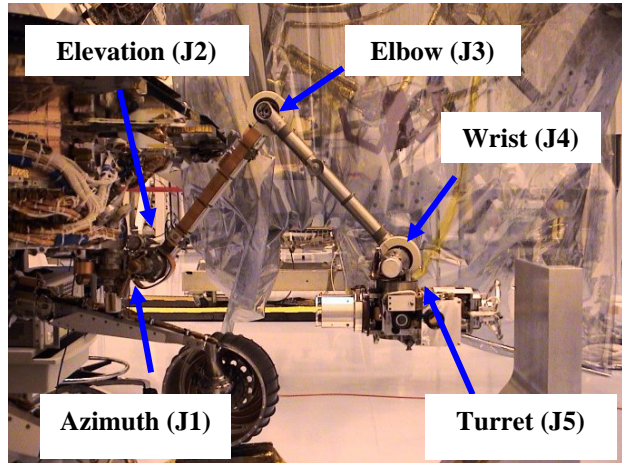surface operations phase of the mission. The paper closes with conclusions in Section 4.
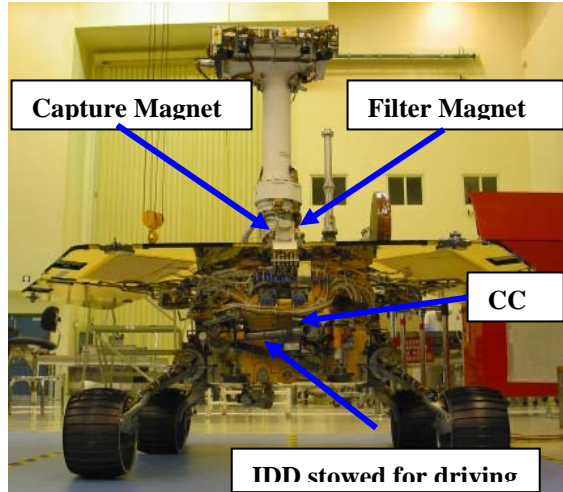

Figure 1 Left, IDD stowed for driving and rover mounted targets, right unstowed IDD with joints labeled

2 Instrument Deployment Device

In this section we present a brief overview of the IDD. For detailed information on the IDD mechanical system and software the interested reader is referred to [6]. The IDD is mounted at the front shelf of the belly of the rover's Warm Electronic Box as shown in figure 1. The IDD weighs approximately 4kg and carries a 2 kg Athena Science payload. The IDD is stowed as shown in figure 1 during rover traverses. Figure 1 depicts the IDD mechanical system with all five joints labeled. Figures 2 depicts the Athena Science Payload as mounted on the IDD turret. Each of the in situ instruments is equipped with a proximity sensor (contact sensor) to detect contact between the instrument and any target, be it the rover, IDD or Martian surface. The MI, MB and RAT, contact sensors are configured to be dual redundant per instrument. The APXS on the hand has two independent contact sensors. The first contact sensor is used to detect successful opening or closing of the APXS dust door and the second is only activated if the door is latched open. There are three rover-mounted targets as shown in figure 1, Compositional Calibration Target (CCT), Capture and Filter Magnets. The Capture and Filter permanent magnets are designed to attract dust from the Martian atmosphere. The CCT is magnetite calibration target for the MB. It is also used to open the APXS dust door for APXS placement on soil targets. A fourth target is mounted on the forearm of the IDD and it is called the RAT brush station.

The IDD employs a distributed control system architecture with functions implemented in hardware and flight software modules. The rover-computing platform is a VME chassis with a RAD6000 running VxWorks real-time operating system. The IDD flight software module contains both low-level and high-level control functionalities such as actuator current limiting based on temperature and pose, inverse kinematic cartesian control, deflection compensation due to gravity and tilt induced droop, model-based pre-loading of instruments on hard targets, instrument placement using proximity feedback sensors, etc.
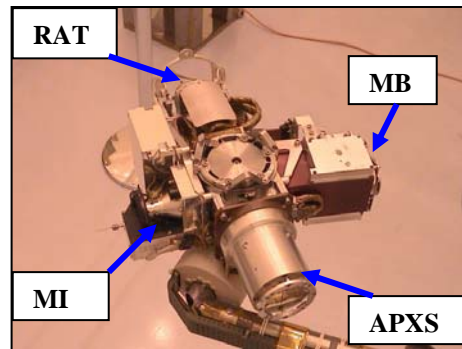

Figure 2 Layout of Athena Science Payload mounted on the IDD turret.

2.1 Instrument Placement Behaviors

In this section we describe the IDD motion behaviors that are used by the Rover Planners to build an IDD sequence.

1. IDD Joint Motion: Coordinated motion of IDD joints with respect to absolute or relative joint angles
2. IDD Cartesian Motion: Coordinate motion of IDD joints that achieves motion of the chosen instrument in 3D position (X, Y, Z) and 2D orientation (azimuth and elevation) with respect to a rover absolute, a rover relative or an instrument (tool) coordinate frame

IDD motions described above can be operated in the following modes.

IDD Motion Modes
   a) Free-Space Motion: IDD motion when no instrument contact is expected; motion terminated at end of

trajectory (no fault) or when unexpected contact is detected (fault)

b) Guarded Motion: IDD motion when chosen instrument is placed in contact with a target; motion terminated at end of trajectory or when expected contact is detected (no fault) or unexpected contact is detected (fault)

c) Pre-Load Motion: IDD motion when chosen instrument is pre-loaded against a target; motion terminated at end of trajectory (no fault) or unexpected contact is detected (fault)

d) Retracting Motion: IDD motion when chosen instrument is retracted from a target; motion terminates at end of trajectory (no fault) or unexpected contact is detected (fault)

3. IDD Tool Change: given the position and orientation of a chosen instrument during the last known guarded motion onto a target, place another instrument at this same position and orientation (combines retraction motion of original instrument, turret rotation to new instrument, and guarded motion of new instrument onto target)

4. IDD Unstow: Move the IDD from the stowed-for-driving position to the "ready" position out in front of the rover using a series of IDD joint-space motions that are stored in a parameter table

5. IDD Stow: Move the IDD from the "ready" position out in front of the rover to the stow-for-driving position using a series of IDD joint space motions that are stored in a parameter table

6. IDD Joint Calibration: Initialize IDD joint position knowledge using actuator hardstops, actuator potentiometers, or ground-seeded positions

The IDD collision checking software is based on the FIDO rover's collision checking software, described in [7].IDD collision checking employs geometric models of the IDD, rover and instruments to determine whether or not a geometric model of the rover or instruments intersects with a geometric model of the IDD. The on-board IDD software performs collision checking prior to initiation of motion at each via point along cartesian and joint-space trajectories. Terrain collision prevention is a ground function.

IDD fault protection has no automatic recovery. All detected faults result in the termination of current command and the preclusion of all future IDD commands until the ground clears the fault condition (IDD motion or goal errors).

3   IDD Command Sequence

IDD command sequence generation is the most complex task of all rover sequence planning. A typical IDD sequence has hundreds of commands and is highly integrated with other rover activities. There is virtually no automation of IDD command sequence generation.

Daily tactical uplink surface operations starts with the science and engineering teams using the Science Activity Planner (SAP) [8] to collaboratively create an Activity Plan during the Science Operations Working Group meeting. The Activity Plan consists of a time-ordered set of engineering and science activities to be performed by the rover over a specified time period usually a Sol (a Martian day, 24 hours, 39 minutes). When the Mission Manager approves the Activity Plan it is subsequently called a Validated Activity Plan. The next step in the process is to partition the Validated Activity Plan and assign specific activities (e.g. imaging, mobility, MB spectra, etc) to members of the Integrated Sequencing Team (IST) to expand into command sequences. The IDD and Mobility activities from the Validated Activity Plan are assigned to the Rover Planners (RP).

The Rover Planners generate an ordered list of commands with associated arguments and control flags that can be executed by the rover onboard sequence engine called a sequence (or command sequence) for Mobility and IDD activities. The sequences built by the RP may "activate" or "run" other command sequences (e.g. cameras, etc) which may run simultaneously with the RP sequence. The RP coordinates with the rest of the IST team to determine the number of sequence(s) required for an activity or activities to satisfy science priorities (e.g. time of day to make observation, etc), avoid conflicts (e.g. resource usage), comply with flight rules, and resource constraints. More often than not the RP sequences are generated from MACROS, a prototype version of ordered list of commands with associated arguments and control flags that perform specific functions e.g. Unstow or Stow the IDD etc. MACROS are used to capture functions that will be repeatedly used during IDD operations and in general require little or no modifications to their template, but may require changes to parameters and control flags associated with their commands. In the case of the IDD there is unique set of MACROS for each rover. All IDD teach point (rover mounted targets) operations are captured in MACROS, e.g. APXS doors opening at the CCT, MB placement on Capture Magnet, etc.

IDD sequences are event-driven; that is, status of the execution control flag of commands determines the behavior of the sequence engine. In order words, the successful completion of preceding commands in a sequence triggers the execution of the next command, this process continues until the last command in the sequence is executed. However, if any command in sequence terminates with failure the sequence is halted by the sequence engine. Another way to think of event-driven sequences is that commands do not have time tags

associated with them that indicate when they are to be dispatched.

IDD sequences also employ conditional sequencing with logical conditionality. This enables the RP to sequence the IDD such that a secondary set of commands (e.g. preclude IDD activities) would be executed depending on if predefined conditions are not satisfied. For MER the variables that are compared in conditional sequencing constructs are called Defined Data Items (DDI). Defined Data Items use is restricted within a sequence and cannot be used across Sols, i.e. they are valid in operations on the same Sol. The IDD has only one Defined Data Item, OK_TO_IDD which has values TRUE/FALSE. This presents several challenges when developing conditional sequences for IDD activities. IDD conditional sequences also employ a generic Defined Data Item called LAST_COMMAND_STATUS with values SUCCESS/FAILURE. Below we present an example of IDD conditional sequence for placement of the RAT in preparation for brushing or abrading a rock surface. The need for a conditional sequence in this example is to ensure that the RAT contact switches are tripped, thus confirming the RAT is in contact with the rock of interest before preloading the RAT and initiating brushing or grinding. There are no Defined Data Items for the state of the RAT contact switches. As a result we developed the following conditional sequence by exploiting unique combinations of two IDD motion behaviors;

The sequence below (table 1) is event-driven. We start with the nominal path through the sequence. If command 1 is successful, that is the IDD motion is either terminated by the RAT contact switch (switches) or commanded position. OK_TO_IDD will be set to TRUE (command 2) and it

```
1.IDD GUARDED MOVE RAT
2.IF OK_TO_IDD EQ TRUE
    2.1 IDD FREESPACE MOVE RAT
3.ELSE
    3.1 PRECLUDE IDD ACTIVITY
    3.2 TERMINATE THIS SEQUENCE
4.ENDIF
5.IF OK_TO_IDD EQ FALSE
     5.1 CLEAR IDD ERRORS
6.ELSE
    6.1 PRECLUDE IDD ACTIVITY
    6.2 TERMINATE THIS SEQUENCE
7.ENDIF
8.IDD PRELOAD MOVE RAT
9.NEXT_COMMAND
```

Table 1 An example of IDD conditional sequence

proceeds to command 2.1 and skips the commands following the ELSE until it finds the ENDIF. The status of command 2.1 would set OK_TO_IDD to FALSE because by design IDD FREESPACE move cannot follow an IDD GAURDED MOVE (if the selected tool contact switch

trips). This means command 5 is TRUE so it proceeds to command 5.1 to clear the anticipated IDD errors to allow IDD use. It skips the ELSE until it finds the ENDIF and then moves to execute command 8 and if that is successful it moves on to command 9. We now present the off-nominal case. If command 1 fails OK_TO_IDD will be set to FALSE. The sequence then skips command 2.1 until it reaches the ELSE, executes commands 6.1 and 6.2 which precludes further IDD motion and terminates the sequence.

3.1   IDD Activities to Command Sequence

There are four types of IDD activities, "Touch and Goal" Sol, "Spectroscopy" Sol, and ''Scratch and Sniff'' Sol [1]. In touch and goal sol activity the rover performs a quick in situ analysis (MI, and MB or APXS, no brushing or grinding) of surface targets of opportunity within the IDD work volume and drives on the same sol to the next target. Spectroscopy Sol activity entails detailed in-situ analyses on high-priority science target with the MI, MB, and APXS. In a Scratch and sniff sol the RAT is used to brush or abrade (expose a fresh) a surface of a rock followed by in situ analysis of the exposed surface with MI, MB and APXS. More often than not a scratch and sniff sol is preceded by a spectroscopy sol on the same target, generally referred to as pre-brush or pre-grind in situ observation.

Before the IDD can be used in any in situ observations two sets of front hazard avoidance camera (hazcam) stereo image pairs must be acquired. One at most 85cm before the final rover position called the penultimate hazcam images (2bits/pixel) and the other at the final rover position referred to as the ultimate hazcam images (4bits/pixel). The penultimate image pair is used to verify that the IDD work volume is clear of any obstacles that might impede or interfere with the IDD deployment. The ultimate front hazard camera image is used to select science features and targets for in situ instruments placements. Targets are 3D locations on a terrain that are selected from stereo image pairs and are used as parameters in activities to perform remote and in situ observations [8]. All targets must be associated with a feature. Features are also 3D locations on a terrain but cannot be used as parameters in activities. They are used to conveniently group targets and define a region on a terrain. Thus a feature can have multiple targets associated with it. On MER each hazcam stereo image pair has associated derived products such as range maps, surface normal map, and reachability maps for each in situ instrument etc. Reachability maps [10] are key to IDD operations; each point in a reachability map represents a position that the IDD can place an in situ instrument(s) without violating any IDD operations constraints such as self collision, collision with rover, terrain and instruments. The reachability maps for any combination of instruments can be fused into a single reachability map. All IDD targets are selected from reachability maps overlaid on associated front hazcam images.

All IDD activities have science targets embedded in them. The following is an example of IDD activity from the Spirit rover. IDD Activity on Sol 225: The IDD activity listings from the approved Validated Sequence Plan are as follows;

1. Unstow the IDD
2. Perform an eight RAT brush mosaic centered on target Apachi on feature Clovis.
3. Post-RAT brush, place the APXS at the center of the RAT brush mosaic for a short integration. Acquire a documentation hazcam image of the placement.
4. Retract the APXS from the center of the RAT brush mosaic
5. Acquire 1x1x5 MI images of the center of the RAT brush mosaic and acquire a documentation hazcam image.
6. Stow the IDD

To generate IDD command sequences for the above activities. First, the RP imports the targets from SAP into the Rover Sequencing and Visualization Planner (RSVP) tool [9]. The RP then performs initial planning of the IDD to place the various in situ instruments identified in the IDD activity on the science target(s). If the RP needs to refine the science target(s) due to resource issues or IDD configuration problems the RP contacts the Chair of Science Operations Working Group to workout the issue(s). The RP proceeds to perform detailed planning (generate commands) of the IDD to reach the selected science targets within resource constraints for the planning cycle. The RP uses the RSVP tool in this endeavor. RSVP provides high-fidelity 3D modeling of the IDD, rover, instruments and terrain and detailed simulations of IDD motion which is driven by the GDS version of the IDD flight software including terrain collision detection.

Table 2 shows the number of times the IDD has be unstowed for both Spirit and Opportunity rovers for the first year of the mission.

Table 2 IDD Unstow performed from sol 1 to 365

Rover	IDD UNSTOW
Spirit	58
Opportunity	80

Each of the in situ instruments, do pose unique challenges for the RP to generate command sequences that direct the IDD to position them against the selected surface targets. In the following sections planning strategies used to place each in situ instrument is presented.

3.1.1 MB Placement

MB placement is very simple; it requires the RP to place the instrument into physical contact with the selected science target to enable in situ spectra acquisition. The MB does not require any unique actuations for placement on rock or soil.

The RP positions the MB 10cm above the target and moves the MB in tool frame along an approach vector up to 11cm using IDD guarded move to contact the target and if necessary preloads it against the target (~5N). The MB has been solely used to reliably handle position uncertainty with respect to surface targets (rock/soil) by overdriving the MB along an approach vector up to 15mm using IDD guarded move (called a MB touch). Once the target position is located subsequent instrument placements use the recorded position. Placement of the MB on rover mounted targets is fairly simple since the RP employs IDD MACROS. Table 1 shows the MB placement for both Spirit and Opportunity rovers for the first year of the mission.

Table 3 IDD MB placements from sol 1 to 365

	IDD MB PLACEMENT				
Rover	Soil	Rock	Capture Magnet	Filter Magnet	CCT
Spirit	32	51	3	1	4
Opportunity	34	52	3	1	3

3.1.2 APXS Placement

APXS placement has special requirements, the APXS dust door needs to be opened. The APXS door can either be opened on the CCT or on a fairly flat and stable rock with surface area of at least ~4 cm sq. A great deal of thought must go into planning overnight APXS placement on soil targets, the dust door must be opened during the day to minimize IDD motion overnight. All overnight IDD motions require heating the actuators to their operations temperature. Another issue with APXS placement over soil targets is that the instrument must not be buried or contact the soil it must hover a few millimeters (3mm) above target to avoid contaminating the sensor head. This problem is easily solved by using the MB to find the soil surface then changing tool to APXS, leaving the APXS ~3mm above the target. APXS placement on rock targets is usual straight forward if the rock can be used to open the dust door. The RP positions the APXS 10cm above the target and moves the APXS along an approach vector up to 11cm using IDD guarded move to open and latch the dust door. Effectively overdriving the APXS by 1cm. When changing tool from another in situ instrument to APXS the differences in tool lengths (and contact switch stroke) must be appropriately accommodated so as not to drive (slam) the APXS into the target. Placing the APXS on rover mounted targets is fairly simply since the RP employs IDD MACROS. Table 3 shows the APXS placement for both Spirit and Opportunity rovers for the first year of the mission.

Table 4 IDD APXS placements from sol 1 to 365

IDD APXS PLACEMENT		

Rover	Soil	Rock	Capture Magnet	Filter Magnet	CCT
Spirit	30	55	3	0	39
Opportunity	18	52	2	1	27

3.1.3 MI Placement

The MI also has a dust cover. Unlike APXS dust door, the MI dust cover is actuated to open/close. The MI dust cover is only opened a few moments before MI image acquisition starts, usually 10cm above the target of interest. To open/close the MI dust cover the RP uses a MACRO. The MACRO employs a conditional sequence with a logical conditionality that checks if the DDI LAST_COMMAND_STATUS equals SUCCESS before initiating the open/close command. The conditionality is necessary to prevent dust from gathering on the MI lens in case the last command before the MI dust cover open/close command fails, usually an IDD command. Such a situation would lead to the MI lens exposed to the martian environment for an extended period of time until ground operators intervene.

MI image sets of rock/soil targets are general acquired in stacks of 3, 5 or 7 at 3mm steps along the MI optical axis up/down from a standoff position above the target. The step size of 3mm was chosen to ensure optimum focus on targets with relief greater than the MI depth of field (~3mm).This approach usual results in at least one focused image. Sometimes MI stacks include a one position stereo pair at an estimated best-focus position usually ~26mm above the surface of interest with a lateral/vertical (x-y plane) offset of ~15mm. In general, a MB touch or MI contact switch (poker) is used to sense the target of interest surface. Post RAT grind or brush, MI acquisition is usually performed using IDD tool change (change tool from RAT to MI). Another, MI image acquisition strategy is a mosaic of MI image stacks. MI mosaic acquisition is best illustrated by an example. For example if the RP is task to acquire a 2x2x5 MI image stacks mosaic of a soil/rock, where 2x2 represents rows x column in x-y plane of the MI tool frame and 5 the number of MI images in a stack . The RP with the help of the science lead selects the center of the mosaic on the target of interest. MB touch or MI contact switch (poker) is used to sense the target of interest surface then retracted to a standoff distance (usually 10cm) above the center of the mosaic with the MI optical axis pointing at the center of the mosaic. The next IDD moves are described in the following steps;

Step1; Perform a tool frame relative move delta +x and +y to place the MI in the +x and +y quadrant of the mosaic
Step 2;   Acquire MI image stacks with one position stereo at the estimated best-focus position.
Step 3; Retracted MI to a standoff position

Step 4; Return the MI to the center of the mosaic (This is necessary because tool frame relative moves are not commutative.)
Step 5; Perform a tool frame relative move delta –x and +y to place the MI in the –x and +y quadrant of the mosaic
Step 6; Repeat step 2
Step 7; Repeat step 3
Step 9; Repeat step 4
Step 10; Perform a tool frame relative move delta –x and –y to place the MI in the –x and –y quadrant of the mosaic
Step 11; Repeat steps 2, 3 and 4
Step 12; Perform a tool frame relative move delta x and –y to place the MI in the x and –y quadrant of the mosaic
Step 13; Repeat steps 2, 3, and 4

The above steps can be repeated for any MI mosaic size by a judicious choice of x and y deltas to perform tool frame relative moves. Table 4 shows the MI placement for both Spirit and Opportunity rovers for the first year of the mission.

Table 5 IDD MI placements from sol 1 to 365

Rover	Soil	Rock	Capture Magnet	Filter Magnet	Trench targets	Others targets
Spirit	**36**	**85**	**6**	**5**	**14**	**3**
No. images	*364*	*1163*	*16*	*18*	*92*	*12*
Opportunity	**43**	**132**	**4**	**4**	**20**	**12**
No. images	*385*	*1694*	*12*	*13*	*46*	*108*

3.1.4 RAT Placement

RAT placement on rocks requires the RP to place the instrument into physical contact with the selected science target and preload the RAT with an appropriate force for the particular IDD configuration to abrade or brush the surface. Before preloading the RAT a conditional sequence described in table 1 is ran to confirm (RAT contact switches are tripped) the RAT is in contact with rock. Post-RAT preload a grind or brush sequence is activated. Another RAT activity is the RAT brush mosaic. This activity has been predominately sequenced on the Spirit rover. The RAT bush mosaic command sequencing follows the steps outline for MI mosaic acquisition. Table 5 shows the RAT placement for both Spirit and Opportunity rovers for the first year of the mission.

Table 6 IDD RAT placements from sol 1 to 365

Rover	IDD RAT PLACEMENT		
	Grinding	Brushing	Brushing Station
Spirit	14	41	0
Opportunity	22	9	0

Figure 3 shows a Pancam image of a RAT hole and brush mosaic "brush flower" on a rock called Clovis by Spirit

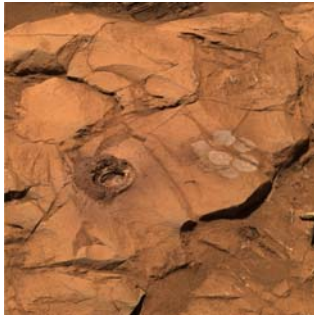rover on sol 226. The IDD activities used to sequence the brush mosaic is described in section 3.1.

Figure 3 Pancam image of a RAT hole and brush mosaic "brush flower" on a rock called Clovis by Spirit rover on sol 226. The IDD activities used to sequence the abrasion and the brush mosaic are described in table 1.

4   Conclusions

In this paper, we have presented extensive details of the in situ operations of the Mars Exploration Rovers 5 degree-of-freedom Instrument Deployment Device (IDD) during surface operations on Mars. The IDD command sequence generation is very labor intensive and complex with a typical sequence comprising hundreds of commands with calls to "activate" or "run" other command sequences (e.g. cameras, MB, APXS, RAT etc) which may run simultaneously with the IDD sequence. Validation of IDD command sequences is laborious and present unique challenges due to the lack of automation. However, the success of the IDD operations on Mars has paved the way for deployment of more advance in situ manipulators for future NASA planetary exploration missions. In addition, it has helped identify technology gaps in operations and deployment of in situ manipulators in planetary exploration. A key technology gap is single command approach and instrument placement.

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