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# NASA Mars 2007 Phoenix Lander Robotic Arm and Icy Soil Acquisition Device

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[1] The primary purpose of the Mars 2007 Phoenix Lander Robotic Arm (RA) and associated Icy Soil Acquisition Device (ISAD) is to acquire samples of Martian dry and icy soil (DIS) by digging, scraping, and rasping, and delivering them to the Thermal Evolved Gas Analyzer and the Microscopy, Electrochemistry, and Conductivity Analyzer. The RA will also position (1) the Thermal and Electrical Conductivity Probe (TECP) in the DIS; (2) the TECP at various heights above the surface for relative humidity measurements, and (3) the Robotic Arm Camera to take images of the surface, trench, DIS samples within the ISAD scoop, magnetic targets, and other objects of scientific interest within its workspace. The RA/ISAD will also be used to generate DIS piles for monitoring; conduct DIS scraping, penetration, rasping, and chopping experiments; perform compaction tests; and conduct trench cave-in experiments. Data from the soil mechanics experiments will yield information on Martian DIS properties such as angle of repose, cohesion, bearing strength, and grain size distribution.

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## 1. Introduction

[2] The Robotic Arm (RA) on the Mars 2007 Phoenix Lander is a 2.4 m long, low-mass, 4-degree-of-freedom arm (Figure 1) that carries on its end effector (Figure 2) the Icy Soil Acquisition Device (ISAD), Robotic Arm Camera (RAC), and the Thermal and Electrical Conductivity Probe (TECP). The ISAD consists of a scoop with two blades for acquiring dry and icy soil (DIS) samples, and a rasp for rapid acquisition of hard icy soils. Very strong icy soil is expected to be encountered ~1 to 10 cm beneath a cover of loose to duricrust-like soil for the chosen landing site [Smith et al., 2008; Arvidson et al., 2008; Mellon et al., 2008]. In this paper we focus on the RA and ISAD since the RAC and TECP are described in detail in companion papers (A. P. Zent et al., The Thermal Electrical Conductivity Probe (TECP) for Phoenix, submitted to *Journal of Geophysical Research*, 2008; H. U. Keller et al., The Phoenix Robotic Arm Camera, submitted to *Journal of Geophysical Research*, 2008). Hereafter we refer to the ISAD and RA as the RA/ISAD system.

## 1.1. RA/ISAD as a Support Instrument

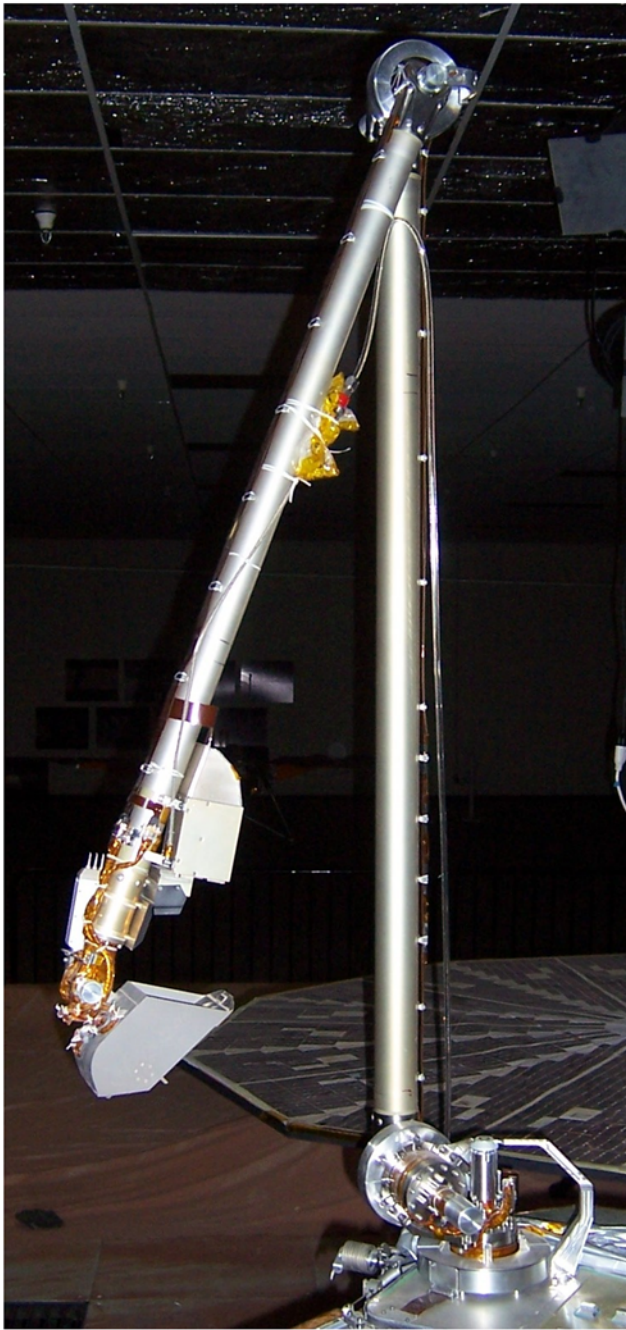
[3] The RA/ISAD is an essential system for achieving the scientific goals of the Phoenix mission by providing support to the other science instruments as well as conducting specific soil mechanics experiments. One of the primary mission goals is to analyze DIS samples in the Thermal Evolved Gas Analyzer (TEGA) (W. V. Boynton et al., The Thermal and Evolved-Gas Analyzer on the Phoenix Mars Lander, submitted to *Journal of Geophysical Research*, 2008) and the Microscopy, Electrochemistry, and Conductivity Analyzer (MECA) (M. H. Hecht et al., Microscopy capabilities of the Microscopy, Electrochemistry, and Conductivity Analyzer, submitted to *Journal of Geophysical Research*, 2008; S. P. Kounaves et al., The 2007 Phoenix Mars Scout Lander MECA Wet Chemistry Laboratory, submitted to *Journal of Geophysical Research*, 2008). The RA/ISAD will support these goals by acquiring both surface soil and subsurface DIS samples from the area in the vicinity of the lander and dumping the samples into the TEGA and MECA inlet ports. The ISAD consists of the following tools: a blade mounted on the front of the scoop opening for scraping up loose to weakly indurated soils (e.g., the dry soils expected to be exposed on the surface), a secondary blade mounted on the bottom of the scoop for preparing hard soils or icy soils for ISAD placement (e.g., duricrust deposits), and a rasp for rapid acquisition of highly indurated soils and icy soils (Figure 2). Subsurface samples will be acquired at varying depths from within trenches excavated by the RA/ISAD, potentially to a depth

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**Figure 1.** The engineering model of the 2.4-m-long Phoenix Robotic Arm (RA) and Icy Soil Acquisition Device (ISAD) is shown in the Payload Interoperability Testbed at the University of Arizona.

of 50 cm depending on the thickness of loose to slightly indurated soils over hard icy soil deposits.

[4] When digging reveals hard icy soil, the secondary blade (located on the bottom of the scoop) will be used to prepare the surface for sample acquisition by the rasp by scraping the icy soil to form a more uniform surface for placement of the ISAD. Once the surface has been prepared, the RA will place the ISAD with the rasp tool in contact with the target area. The RA will then preload the ISAD to

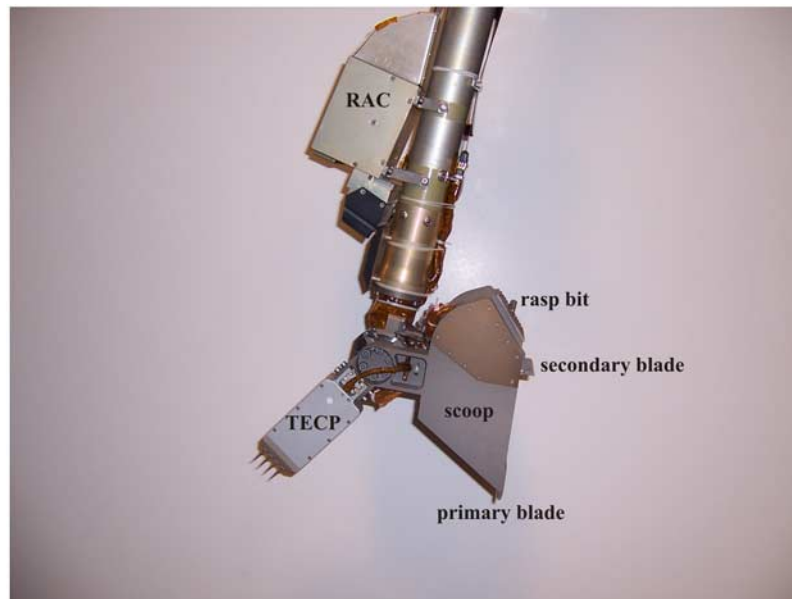
prevent undesired movement during sample acquisition. The rasp cutting tool will then be energized for a brief duration (typically less than 1 min), resulting in acquisition of icy soil. The RA will then relieve the preload on the ISAD and retract it from the surface. Placement and acquisition can be repeated several times in different locations, depending on the amount of sample desired, and the spacecraft resources available. After all acquisition operations have been completed, the sample is transferred to the front of the scoop for imaging by the RAC and dropoff to the analytical instruments. The transfer operation consists of a series of RA motions to move the sample along a number of panels which divide the front and rear chambers of the scoop. During the transfer operation, the rasp cutting tool can be energized, inducing vibrations to aid in the flow of particles.

[5] A key element of the Phoenix instrument suite is the RAC that is mounted on the RA forearm just behind the wrist (Figure 2). Soon after landing the RA will position the RAC to image the lander foot pads to help determine surface properties at the touchdown site. Throughout the mission the arm will periodically position the RAC to take images of the surface, trench floor and end walls, and dumped soil piles. During soil sample acquisition, the scoop will be positioned for the RAC to take close-up images of the DIS samples in the scoop prior to delivery to the TEGA or MECA. There is a specially designed depression in the scoop blade to contain small DIS samples for very close imaging by the RAC at high spatial resolution. The arm will also position the RAC for imaging of the magnetic targets located on the Lander deck, the TEGA and MECA entry ports, nearby rocks, and any other objects of scientific interest within its workspace. We also expect to use the RA to position the RAC to support acquisition of image data to help understand anomalies in the same way that the Viking Lander Imaging System was used to help characterize anomalies during the Viking Lander Mission [Moore *et al.*, 1987]. Support will also be provided to place the TECP probes into DIS surfaces to characterize thermal and electrical conductivities. The RA will also position the TECP to measure atmospheric relative humidity from 0.15 m to 1.8 m above the surface.

## 1.2. RA/ISAD as a Science Instrument

[6] During the surface operations the RA/ISAD will be used along with the other instruments to investigate the physical properties of the surface and subsurface materials in the workspace, using the pioneering Viking Lander work by Moore *et al.* [1987] as a guideline. The primary RA-focused investigation will be direct measurements of DIS mechanical properties using motor currents to determine arm forces during DIS excavations and attempted blade penetrations. Additional information will be obtained from examining the slopes of trenches to determine cohesion and angle of internal friction. Excavated soils will be dumped into piles to observe the angle of repose of disturbed material and the degradation of the pile due to wind erosion. Use of the rasp to acquire icy soil will include examination of telemetry data to understand the strength of these materials and acquisition and analysis of RAC and SSI data to conduct detailed studies of the small trenches excavated by the rasp. Other tasks that will be managed as part of the RA operations are: grouping and categorization of DIS





**Figure 2.** Robotic Arm End Effector tool suite: ISAD consisting of a scoop with primary and secondary blades for scraping and a rasp for acquiring icy soils; RAC for imaging soil and rock targets, instrument ports, and the scoop interior; and TECP for measuring temperature and electrical conductivity.

types, tracking and mapping all workspace activities, and archiving of all pertinent RA/ISAD calibration and operations data for future investigations (particularly for areas where real-time analysis will not be feasible during the mission).

[7] Direct DIS measurements by TEGA, MECA, and TECP will provide additional information for understanding the physical properties and composition of surface and subsurface materials. Additional information will come from RAC and the Surface Stereo Imager (SSI) data. The ability of the RAC to provide close-up imaging of material on the tip of the scoop blade is an example of how the data gathered by another instrument are highly dependent on cooperative operation with the RA/ISAD, in this case to deliver an appropriate sample to the RAC near-focus viewing zone.

## 2. Robotic Arm/ISAD Description

### 2.1. Hardware

#### 2.1.1. ISAD

[8] As already noted the ISAD is a scoop with a front blade for scraping, a secondary blade for scraping indurated materials, and a rasp for acquiring indurated icy soils (Figure 2). The scoop is divided into a front chamber to receive materials excavated by the front blade and a rear chamber that houses the rasp (Figure 3). The two chambers are separated by a sample transfer plate. During digging operations, this plate prevents the majority of scooped material from filling the rear chamber, which could result in jamming of the rasp. This plate also acts to facilitate movement of samples from the rear chamber to the front chamber so that samples acquired using the rasp can be dumped to instruments in the same manner as bulk soil. The plate consists of a vertical and a horizontal shelf, with a slot in the horizontal shelf. This creates a labyrinth through

which material can be transferred from rear to front by rotating the entire scoop about the RA wrist axis. The sample transfer plate is made from aluminum with a clear anodize for abrasion and wear resistance.

[9] The front chamber is used to collect bulk material by scraping or digging with a titanium primary blade. This chamber includes a funnel feature which channels acquired material into a slot, improving the accuracy of sample dropoff (Figure 4). The ISAD scoop and funnel are made of aluminum with a clear anodize for abrasion and wear resistance. This coating on the interior surfaces also reduces



**Figure 3.** Cutaway view of the ISAD showing the rasp, rear and front scoop chambers, and primary and secondary blades.



**Figure 4.** ISAD scoop interior showing the channel used to guide the material sample when delivering to the TEGA and the MECA.

glare when viewing acquired samples with the RAC. A tungsten carbide secondary blade on the bottom side of the ISAD provides a means of penetrating harder materials more easily than the primary blade.

[10] The rear chamber of the ISAD contains a high-speed rasp cutting tool for penetrating hard icy soil and acquiring the cuttings produced during rasping. Acquisition is accomplished by first preloading the ISAD scoop against the surface so that the spring-loaded rasp cutting bit retracts into the scoop. A knurled contact plate grips into the icy soil to prevent motion of the ISAD and RA during rasp operations. The rasp cutting bit is then energized, resulting in rapid penetration of the surface, causing a plume of cuttings to ballistically enter the rear chamber of the scoop. The tungsten carbide cutting bit protrudes from the rear chamber through a slot when the tool is in free space. The rasp cutting bit is mounted within a pivoting housing, allowing the bit to protrude out of the scoop during sample acquisition, as well as to retract fully into the scoop during preloading. Two hard stops constrain movement of this pivot housing. The lower hard stop limits the depth of penetration of the rasp cutting bit. The upper hard stop is positioned in order to allow the cutting bit to fully retract into the scoop. The pivot housing is spring loaded using a torsion spring. The torsion spring acts to force the cutting bit into the material, providing the necessary load on the bit for penetration into icy soil.

[11] The rasp tool is driven by a brushed DC motor. Torque is transferred from the motor shaft to the rasp cutting bit through a set of spur gears and a pair of miter gears, yielding an overall speed reduction of 1.25:1 from the motor

to the bit. The motor is powered by a current-limited on-off circuit, which provides a maximum current to the motor during operation. The device includes three resistive strip heaters that warm the mechanism to allowable operational temperatures. One of the heaters is attached to the motor and the other two are attached to the pivot housing. A temperature sensor on the motor provides ISAD temperature feedback. All components used to power the rasp cutting bit are thermally isolated from the main scoop body by an insulating material. This thermal isolation helps ensure that the icy soil samples are kept cold, thus minimizing loss due to sublimation.

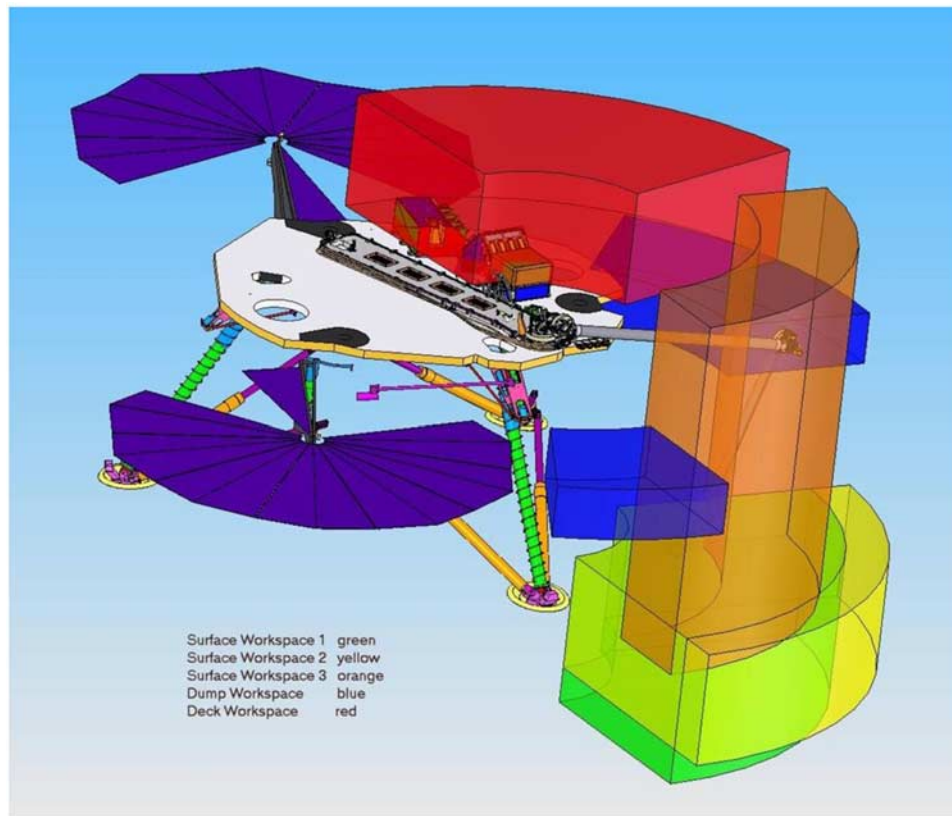
[12] The rasp setup includes a capability to vibrate the ISAD to help move samples from the rear chamber of the scoop to the front, and for improving the transfer efficiency from the front funnel to the instrument inlet ports. The vibration mechanism is only engaged when the rasp cutting bit is in its rest position against the lower hard stop. A cam feature attached to the rasp cutting bit engages a low-friction surface, which is grounded with respect to the scoop. As the rasp bit rotates at high speed, the cam feature causes the pivot housing to oscillate such that the spring-loaded housing impacts the lower hard stop once per revolution, causing high-frequency vibration.

#### 2.1.2. RA

[13] As noted, the RA (Figure 1) is a 4-degree-of-freedom manipulator with a back-hoe design that provides motion about shoulder yaw (azimuth), shoulder elevation, elbow, and wrist pitch [Schenker *et al.*, 1995]. The arm links are made of aluminum with titanium end fittings. The end effector consists of the forearm-mounted RAC, and the ISAD and TECP mounted on the wrist (Figure 2).

[14] The joint actuators consist of brushed DC motors with multistage speed reduction consisting of planetary gears and a harmonic drive (except the wrist, which has a bevel gear at the output of the planetary gears). Braking is achieved by actively shorting the motor leads to slow the motor until magnetic detents capture the rotor. The detents provide sufficient holding torque to assure no slippage while power is off. Position sensing is accomplished via quadrature encoders at the motor shaft and potentiometers at the joint output. The encoder counters can be initialized on the basis of potentiometer data or can be set by running each joint up against a known mechanical hard stop located at the end of each joint's travel. The encoder counts are stored in flash memory at the end of each day for use during initialization the following day. Each joint is equipped with a heater and temperature sensor to assure that the motor operation is conducted at or above minimum operating temperature. The RA workspace is depicted in Figure 5.

[15] The RA Electronics (RAE) consists of two printed circuit boards located in the Payload Electronics Box (PEB) and provides power conditioning; motor voltage control and drivers; heater drivers; joint encoder counting; and analog-to-digital conversion of potentiometer voltages, temperature sensor voltages, motor currents, and total heater current. In addition a board mounted externally on the PEB limits the current to the rasp to prevent overheating. The RAE provides the interface to the Lander Command and Data Handling (C&DH) computer over a serial link. Firmware running on the RAE microprocessor provides for low-level motor command execution to move the joints to the specified



**Figure 5.** Robotic Arm workspaces: the green and yellow spaces are the regions where digging, scraping, rasping, and inserting the TECP (yellow only) into the soil will be done; the blue space is the primary area for dumping the material excavated during trenching; the red space is the area over the deck where the sample delivery to the TEGA and MECA occur along with imaging the instrument ports with the RAC; and the orange space is the region through which the acquired samples are transported to the instruments.

positions, heater and rasp command execution, analog-to-digital calibration, and sensor monitoring.

[16] To prevent contamination of the Martian subsurface with Earth organisms per NASA planetary protection policy, the RA meets Category IV-B bio-burden requirement (NPR 8020.12B Planetary Protection Provisions for Robotic Extraterrestrial Missions, Revision B, 16 April 1999) in order to meet this requirement, the RA was sterilized prior to final integration onto the lander and encased in a biobarrier (Figure 6). The biobarrier maintains sterilization during the journey to Mars and is deployed shortly after landing on the Martian surface.

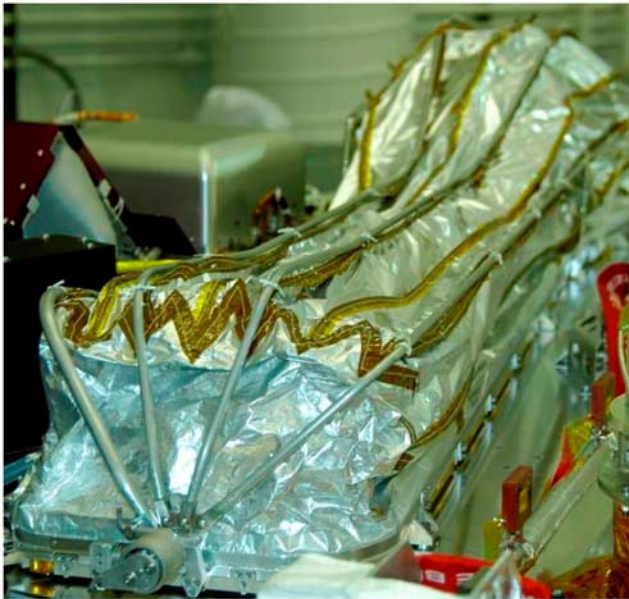
## 2.2. Software

[17] The RA flight software resides on the Lander Command and Data Handling computer and provides the following functions: (1) initialization (load parameter table, collision object database, and state files; request power on); (2) expansion of high-level task commands; (3) generation of arm movement trajectories; (4) validation of collision-free motion paths; (5) control of arm motion, joint heaters, and rasp; (6) setting parameters (e.g., motor current limits) in the RAE; (7) reading sensor data and monitoring the arm status; (8) fault detection and recovery; and (9) sending arm sensor data to telemetry.

[18] The RA has a full suite of arm motion commands that provide for coordinated joint motion as well as Cartesian motion of the end effector [Taylor, 1979]. Joint moves can be specified as either absolute moves or relative moves to the current position. Cartesian moves can be specified as absolute or relative moves with respect to the payload coordinate frame located at the base of the RA. The operator can also specify Cartesian motion in the local frame of the currently selected tool (scoop, scraping blade, TECP, rasp load plate, or RAC). The four degrees of freedom for Cartesian position are specified as the three translation coordinates plus the angle that the currently selected tool approach vector makes with the plane of the lander deck (except for the RAC whose orientation cannot be controlled separately). Each motion command is broken up into a series of via points that are sent sequentially to the RAE for execution by the firmware.

[19] The arm can also be commanded to perform more complicated tasks such as digging a trench or acquiring a sample using the scoop by a single command. The software expands the high-level command into the appropriate set of motion commands which are executed sequentially. This approach saves uplink bandwidth and eases the burden on the operator in developing complicated command sequences. The software also tracks time and energy resources





**Figure 6.** Robotic Arm encased in the biobarrier that maintains sterility to prevent contamination of the Martian subsurface with Earth organisms. The biobarrier is held in place by a series of latches that are released shortly after landing by a pyro-activated pin puller. Torsion springs at each end then rotate the ribs (right to left in the figure) to open the bag.

used during command execution and will gracefully terminate operations when allocations are exceeded. This feature will be most useful when digging a trench due to the uncertainty of the soil properties that affect the execution of the dig trench command.

[20] In addition to providing for control of the free-space arm motions, the software is also capable of executing guarded moves where the arm will move toward its commanded position until contact is made. This is accomplished by monitoring motor currents and computed joint torques versus preset thresholds. Guarded moves will be employed when inserting the TECP into the ground, preloading the rasp load plate on a hard icy surface, acquiring samples, and digging trenches. Thus, RA operation is robust with respect to surface location uncertainty.

[21] To aid in safety and increase autonomy, the RA software is capable of detecting and recovering from faults and anomalous events. Faults and events are defined as follows: (1) fault, inability to complete a command due to failure of hardware (sensor, actuator, electronics, etc.); and (2) event, inability to complete a command due to anything other than a fault (e.g., arm motion impeded by a rock in the digging path).

[22] If a fault or event is detected, the fault or event type is reported in telemetry. Depending on the fault or event detected, the RA software will either attempt to recover from the fault or event or place the arm in a safe configuration. It is expected that the RA will occasionally encounter conditions that impede its motion during digging (a rock in the soil, encountering the icy soil table, etc.). The

software has a built-in accommodation algorithm, similar to the one reported by Bonitz and Hsia [1996] to compensate for this condition by adjusting the scoop trajectory and, if necessary, dumping the scoop contents and reexecuting the digging motion.

[23] The primary operations tool for commanding the RA will be the Rover Sequencing and Visualization Program (RSVP) [Cooper, 1998] used on Pathfinder and the Mars Exploration Rover projects and adapted for Phoenix. RSVP provides target designation from panorama image data, generates command subsequences via programmed macros, simulates arm motion, checks for collisions, estimates command durations, and outputs a complete command sequence file for uplink to the Lander.

### 3. Development Testing and Calibration

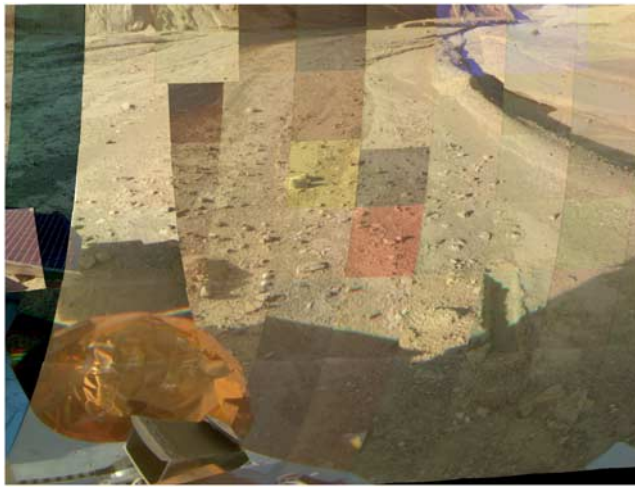
[24] The RA and ISAD were extensively tested during development to verify that the design could withstand the harsh environmental conditions expected as well as to characterize the performance of the actuators and to calibrate the sensors and kinematic model of the arm. Qualification testing included both vibration testing to simulate launch loads and thermal vacuum testing to simulate the Martian environment (temperature and pressure).

#### 3.1. RA

[25] The performance of the RA actuators was evaluated over the expected operating temperature range, operating voltages, and loads. Data from the characterization were used by the control system to continuously monitor joint torques for use in executing guarded moves, in the accommodation algorithm and to prevent excessive torque from damaging the joints. The joint output torques were derived by first computing the no-load motor currents which are both temperature- and voltage-dependent and then computing the torque from the actuator torque constant. During the landed mission, a standard set of free-space moves will be periodically executed to monitor actuator performance. In addition, the joint heaters will be operated to characterize the thermal properties of the joints in the Martian environment.

[26] Calibration of the RA kinematic model was done by moving the arm through a series of poses throughout the workspace and measuring the location of the end effector using a laser tracker. The kinematic model parameters were then determined by solving a constrained minimization problem that minimizes the mean error over the measured poses. The kinematic model parameters are based on the method of Denavit and Hartenberg [1955].

[27] During digging and soil mechanics experiments, estimates of forces exerted by the end effector tools will provide important data for use in determining soil properties. These estimates can be made from the sensed motor currents, but will be somewhat crude due to unmodeled arm dynamics and the limited degrees of freedom of the arm. During digging and soil mechanics experiments, reaction from the soil can exert force on the end effector that cannot be detected at the arm joints via the sensed motor currents due to the limited degrees of freedom and the fact that all of the motors are not on at all times during arm motion.



**Figure 7.** Trench dug by the MVACS Robotic Arm in Death Valley in hard soil with a resistance up to 7 MPa as imaged by the MVACS Surface Stereo Imager. The trench is 0.10 m deep by 0.48 m long by 0.15 m wide and took 233 min to dig.

### 3.2. ISAD

[28] In addition to vibration and thermal qualification testing, the ISAD was dynamometer tested to characterize the output torque of the tool across the expected temperature range, as well as to determine the downward force on the cutting bit through its range of motion.

[29] The Engineering Model ISAD was tested extensively in a thermal vacuum chamber at Mars ambient conditions to characterize the sample acquisition ability of the mechanism, and the sample transfer efficiency in moving particles from the rear chamber to the front chamber using RA wrist motions. A mockup of the RA was constructed, consisting of a gantry system with three degrees of freedom; linear translation, preload capability and simulated wrist motion. A tool for measuring sample volume was attached to the front of the scoop in place of the primary blade. A camera inside the chamber was used to image the inside of the scoop and the volume of sample produced so that multiple tests could be conducted without requiring access to the inside of the chamber.

[30] Three simulants were tested, all cooled and maintained at approximately  $-120^{\circ}\text{C}$ , while the ISAD was maintained at approximately  $-30^{\circ}\text{C}$ . The simulants included icy soil consisting of JSC Mars-1 simulant and 30% by weight water, icy soil with embedded basalt fragments covering 20% of the surface, and pure ice. The sample acquisition capability of the ISAD was characterized by removing the panels separating the front and rear of the scoop, running the rasp cutting tool, and measuring the volume of sample acquired in the scoop. The sample transfer efficiency was determined by comparing the volume of sample that reached the front chamber of the scoop to the total amount of sample acquired. The ISAD vibration mechanism was energized for testing of sample transfer efficiency. At each RA wrist sample transfer position, the ISAD vibration mechanism was powered on for 30 s to move particles over transfer surfaces. The ISAD was able to

transfer an average of  $0.5\text{ cm}^3$  of material from the rear to the front chamber per placement and operation of the rasp cutting tool, with the sample transfer efficiency of approximately 60% to 80%. The variability in the sample transfer efficiency was largely due to whether or not fine particles grouped together to form larger particles, which pass through the transfer panels with greater difficulty. Although some particles were occasionally left in the rear chamber, running the RA wrist through the transfer angles once more typically cleared the rear chamber in preparation for the next sampling operation. The average cutting duration from initial turn-on of the sample acquisition device to the time at which it reached its “lower” hard stop was approximately 16 s in icy soil and icy soil with rocks, and 6 s in pure ice. After testing to the expected operational lifetime of the rasp of 60 min, further sampling tests were performed. For these tests the duration of cutting increased to an average of 37 s for all materials due to wear of the tungsten carbide cutting bit.

[31] Along with the calibration and qualification testing, additional digging tests were performed in the test bed and in the field. The Phoenix RA design is largely inherited from the Mars Volatiles and Climate Surveyor (MVACS) RA on the Mars Polar Lander [Bonitz *et al.*, 2001]. The MVACS RA digging capability was demonstrated in field testing in Death Valley in January 2000. Figure 7 shows the trench dug by the MVACS arm during the field test in



**Figure 8.** Trench dug in fine basaltic sand by the RA in the Payload Interoperability Testbed at the University of Arizona. The trench is 0.125 m deep by 0.4 m long (at the bottom) by 0.17 m wide and took 52 min to dig.





**Figure 9.** Tailings from trench produced in the Payload Interoperability Testbed. The pile is approximately 0.07 m high by 0.46 m in diameter with an angle of repose of 0.62 rad.

conglomeratic soils cemented by caliche. On site cone penetrometer measurements showed normal stress resistances up to 7 MPa, the highest values of approximately 100 tests made in Death Valley and the Mojave Desert soils. The MVACS RA Death Valley experiment certainly validated the capability of the RA to dig in the types of loose soils and duricrust expected for the Phoenix mission. Additional digging has been conducted in unconsolidated soil with the Phoenix RA in the Payload Interoperability Testbed (PIT) at the University of Arizona using a poorly sorted, fine to medium basaltic sands as a soil analog (Figures 8 and 9).

[32] I. Campbell from New Zealand has demonstrated that by carefully shaving the vertical walls of a trench in the dry valleys he has been able to photograph the layering in the soil clearly enough to make some important findings relating to volatile movement and saltation [Campbell *et al.*, 1998]. Using the RAC and this technique, we expect to be able to discern the fine-scale layering expected at the Phoenix landing site. An example of this type of image can be seen in Figure 10 which shows the sidewall of trench dug using an end effector mockup in the Antarctic Dry Valleys by MVACS team members 1999.

#### 4. Experiment Investigations

[33] Data acquired as part of the DIS physical properties experiments will come from many sources. A majority of the RA operations will be in support of the primary mission objectives including: digging, rasping, dumping, and acquiring DIS samples, and TECP insertion and placement. Although these activities will not be performed specifically to provide materials properties data, by tailoring the operational sequences carefully it will be possible to leverage these data with information from other instruments to gain additional insight into physical properties. For example, by maintaining a constant dump location for a few hours of operation while digging a trench, a rather sizable soil conical pile can be obtained. In order for this pile to be useful for observing changes over time, it should be in an

isolated area, which necessitates moving the dump location for future digging to another area. This means extra effort in managing the available workspace as a resource, as well as the additional wear on the actuators for the additional movement. Another example of tailoring operations to maximize data content is the choice of the azimuthal angle for digging a trench. There is only a small range of azimuth angles that allows the SSI to image directly down the length of the trench. In order to optimize viewing by the SSI, primary trenching operations will be performed at this digging angle if surface conditions permit.

[34] Another science tradeoff made on a daily basis will be the volume of digging and rasping data that are sent back to Earth. Because of resource limitations of the lander it may be necessary to decrease the RA data collection rate to obtain extra imaging or other data. These decisions will be made on the basis of the relative value of the data as determined by the science team, and will be heavily influenced by the relative quality of the data sets and their contribution to the overall mission goals. For example, if the soil is relatively loose, thick, and uniform, then extra images would be more useful than digging data collected at a high sample rate for determining soil characteristics.

[35] In addition to the data gained during regular arm operations, specific materials properties experiments will be performed. Because of the criticality of the efficient operation of the arm to support the rest of the science objectives (particularly acquiring samples for the MECA and TEGA), dedicated materials properties experiments will only be



**Figure 10.** Sidewall of trench manually dug with an end effector mockup by MVACS team members in an Antarctic Dry Valley in 1999 showing fine-scale layering.

conducted when resources are not needed by higher priority activities. However, even under adverse conditions it should be possible to perform a substantial number of dedicated experiments. The following is a partial list of some of the physical properties experiments that will be conducted:

[36] 1. ISAD blade and TECP pin insertion to determine DIS penetration resistance. The leading edge scoop blade will be used to approximate the insertion of a two-dimensional plane to obtain similar data. The TECP sensor pins will be inserted into DIS surfaces at a number of locations. The amount of insertion will be used to infer material resistance.

[37] 2. ISAD loading experiments. It will be possible to explore surface deformation by imaging the indentations made by placing the ISAD baseplate and rasp onto the surface and applying a modest load from the RA.

[38] 3. Scraping with the primary and secondary scoop blades. The cutting ability of the primary blade and the ability of the secondary blade to scrape surfaces will yield information on the cohesion of DIS materials. Close-up imaging of wear on the scoop blades will provide DIS strength data. If the opportunity is presented, rocks within the workspace will be abraded using the tools on the ISAD to infer material properties.

[39] 4. Intentionally causing trenches to cave in. By undercutting the wall of the trench or by using the underside of the scoop to apply pressure at the surface next to the edge of the wall it will be possible to cause a trench wall to cave in under controlled conditions, yielding information on bearing strength, angle of internal friction, and cohesion.

[40] 5. Chopping soil samples. The ability of the arm to repeatedly chop a sample in preparation for TEGA delivery will provide cohesion data. This capability can be used with any of the end effector tools (except the RAC and TECP) allowing for many possible experiments that provide material property information.

[41] 6. Shaking/rasping the end effector. Because of the flexibility and length of the arm it is possible to create repeatable agitations to shake particles loose, allowing for insight into particle adhesion. RAC-based imaging of samples in the scoop before and after rasp-induced vibrations will allow characterization of the extent to which particles were moved by the vibrations.

[42] 7. Excavated soil piles. Long-term data will be gathered by monitoring the evolution of purposefully placed conical excavated soil piles, searching for evidence of wind action and possible frost accumulation.

[43] 8. Icy soil exposure. Dry soil will be removed from the surface, thereby exposing the icy soil surface. This surface can be examined and monitored over time as the ice sublimates.

## 5. Data Products

[44] The RA/ISAD subsystem generates two kinds of telemetry: engineering and science. Engineering telemetry consists of arm state data that are downlinked at the completion of each RA command. Science telemetry consists of detailed sensor data collected at a programmable rate during command execution. RA/ISAD science telemetry is

used for reconstruction of the digging process, soil mechanics experiments and for troubleshooting.

[45] The following engineering data are reported to the telemetry system at the completion of each RA command (except where noted): (1) command op code; (2) joint position from encoders (radians); (3) joint position from potentiometers (radians); (4) joint and rasp temperatures (degrees Celsius); (5) sum of heater and rasp currents (amps); (6) energy consumed (watt hours); (7) voltage references (volts); and (8) health status (fault and event error logs).

[46] While the arm is moving, raw arm sensor data are collected and stored for subsequent downlink in telemetry. All analog data are converted to digital format. The following raw digitized data are collected: (1) joint angle encoder count; (2) joint angle potentiometer voltage; (3) joint and rasp temperatures; (4) motor currents; (5) motor voltages; (6) status word (motor, brake, and heater state information); (7) sum of heater and rasp current; and (8) time.

[47] The RA science telemetry will be the most useful for scientific analysis of soil properties during digging and soil mechanics experiments. The motor currents along with the reconstructed arm trajectories will yield information regarding the degree of difficulty of digging in the various soils encountered and of executing the arm motions during the various soil mechanics experiments. In addition to the data listed above, detailed history of the arm state and control variables for the last 30 s of operation is downlinked whenever a fault or event occurs. This will permit reconstruction of the exact sequence of events leading to the anomaly.

## 6. Conclusion

[48] The Mars 2007 Phoenix Lander RA/ISAD system is an essential element for carrying out Phoenix science experiments. In support of the other instruments this system will dig trenches in the Martian loose and crusty soil, rasp highly indurated and icy soils, deliver particulate samples to the MECA and TEGA, and position the TECP and the RAC. The RA/ISAD will also conduct arm-specific science experiments to collect data relating to soil properties such as periodic imaging of dumped soil piles, surface scraping and soil chopping experiments, compaction tests, insertion of the blades into the surface, shake tests and trench cave-ins. Key data elements include joint motor currents and trajectories, which will be used to estimate end effector forces during arm operations. Data from the RA/ISAD support operations and science experiments and, when combined with data from the other instruments, will yield important information on Martian soil and icy soil properties.

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