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InSight Mars Lander Robotics Instrument Deployment System

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Abstract The InSight Mars Lander is equipped with an Instrument Deployment System (IDS) and science payload with accompanying auxiliary peripherals mounted on the Lander. The InSight science payload includes a seismometer (SEIS) and Wind and Thermal Shield (WTS), heat flow probe (Heat Flow and Physical Properties Package, HP^3) and a precision tracking system (RISE) to measure the size and state of the core, mantle and crust of Mars. The InSight flight system is a close copy of the Mars Phoenix Lander and comprises a Lander, cruise stage, heatshield and backshell. The IDS comprises an Instrument Deployment Arm (IDA), scoop, five finger "claw" grapple, motor controller, arm-mounted Instrument Deployment Camera (IDC), lander-mounted Instrument Context Camera (ICC), and control software. IDS is responsible for the first precision robotic instrument placement and release of SEIS and HP^3 on a planetary surface that will enable scientists to perform the first comprehensive surface-based geophysical investigation of Mars' interior structure. This paper describes the design and operations of the Instrument Deployment Systems (IDS), a critical subsystem of the InSight Mars Lander necessary to achieve the primary scientific goals of the mission including robotic arm geology and physical properties (soil mechanics) investigations at the Landing site. In addition, we present test results of flight IDS Verification and Validation activities including thermal characterization and InSight 2017 Assembly, Test, and Launch Operations (ATLO), Deployment Scenario Test at Lockheed Martin, Denver, where all the flight payloads were successfully deployed with a balloon gravity offload fixture to compensate for Mars to Earth gravity.

Keywords Instrument placement · Robotics in situ · Robotic arm geology

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Fig. 1 InSight Spacecraft Lander and Cruise Stage at Lockheed Martin Space Facility in Littleton Colorado

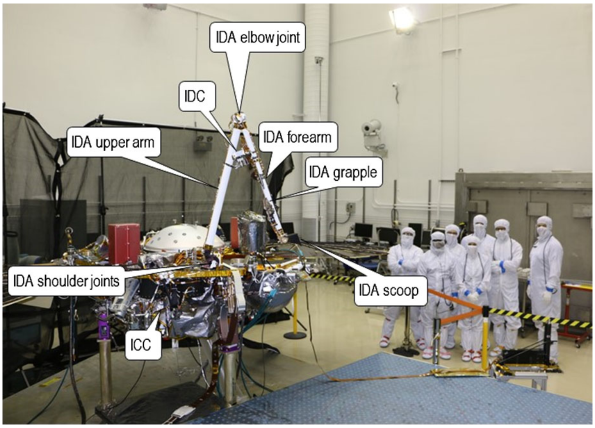


Fig. 2 InSight Mars Lander with IDS Elements labeled

1 Introduction

The InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) mission is a Discovery Program lander to investigate the internal structure of Mars and the differentiation of the terrestrial planets (Banerdt et al. 2018). The InSight flight system is a close copy of the Mars Phoenix Lander and comprises a Lander, cruise stage, heatshield and backshell. The Lander subsystem (shown in Fig. 1) is the core of the flight surface system and controls all functions throughout the mission phases. The InSight Instrument Deployment System (IDS) (shown in Fig. 2) and science payloads with accompanying auxiliary peripherals are mounted on the Lander. The InSight science payload includes a seismometer (SEIS, Lognonné et al. 2018) and Wind and Thermal Shield (WTS), a heat flow probe (Heat Flow and Physical Properties Package, HP^3, Spohn et al. 2018) and a precision tracking system (RISE, Folkner et al. 2018) to measure the size and state of the core, mantle and crust of Mars.

This paper describes the design and operations of the Instrument Deployment Systems (IDS), a critical subsystem of the InSight Mars Lander necessary to achieve the primary scientific goals of the mission including robotic arm geology and physical properties (soil mechanics) investigations at the Landing site.

Table 1 IDS Driving Requirements

	IDS driving requirements
1	The IDA shall operate for 4 hours and for 111 Martian sols plus 10 hours for ground testing
2	The IDS shall positively capture and retain deployable elements, including under loss of power, until placement on the surface is confirmed
3	The IDS shall deploy elements to the surface with the Lander deck tilted 15 degrees w.r.t. gravity
4	The IDS shall have a total mass of less than or equal to 9.41 kg
5	The IDS shall be able to lift a mass of up to 9.5 kg
6	The IDS shall acquire ICC images of the IDA workspace within the FOV of the ICC
7	The IDC Field of view shall include the IDA end-effector during capture and disengagement from deployable elements
8	The IDA shall have repeatability of 0.005 m
9	The IDA shall position the end effector with an absolute error of less than or equal to 0.015 m
10	The IDS shall determine the IDC imaging baseline to within 0.0028 m
11	The IDS shall acquire images of the Lander deck and Solar panels within the field of view of the IDC

2 Instrument Deployment System (IDS)

The InSight Instrument Deployment System (IDS) consists of the Instrument Deployment Arm (IDA), scoop, five finger "claw" grapple, motor controller, arm-mounted Instrument Deployment Camera (IDC), lander-mounted Instrument Context Camera (ICC), and control software (Fig. 2). IDS is responsible for the first precision robotics instrument placement and release (seismometer and heat flow probe instruments) on a planetary surface that will enable scientists to perform the first comprehensive surface-based geophysical investigation of Mars. Table 1 lists the IDS driving requirements.

2.1 Instrument Deployment Arm (IDA)

The InSight IDA is a refurbished flight robotic arm from Mars Surveyor 2001 Lander mission (Bonitz et al. 2000). The IDA is a four degree-of-freedom back-hoe design manipulator with a 1.8-m reach that provides the following motion: yaw (shoulder azimuth, joint 1) and three pitch joints (shoulder elevation, elbow, and wrist, joints 2 through 4, respectively). The IDA links are made of titanium. During normal operations the IDA actuators are capable of generating 35, 120, 65, and 10.5 Newton-meters of torque at the joint output for joints 1 through 4, respectively. The IDA can lift and deploy a 9-kg payload on Mars (33 N) at 1.65 m distance. The force the IDA end-effector can exert is configuration dependent, but the average force is typically about 80 N.

Each joint has a temperature sensor and heater and includes a dust seal to prevent contamination of the motor and gearbox. The IDA is designed to withstand expected environmental temperatures from $-110°$ to $+70$ °C, in a CO_2 atmosphere, with pressure as low as 5 Torr. Each of the IDA joints consists of a brushed DC motor with two-stage speed planetary gears and a harmonic drive at the output (except the wrist, which has a bevel gear at the output of the planetary gears). The IDA joints do not have a mechanical braking systems but employ a dynamic braking system where actively shorting the motor leads slows the motor until magnetic detents capture the rotor. The magnetic detents are sized to provide the appropriate holding torque to assure no slippage while the IDA is powered off. Each joint has two position sensors: encoders on the joint input motor shaft and potentiometers at the joint output

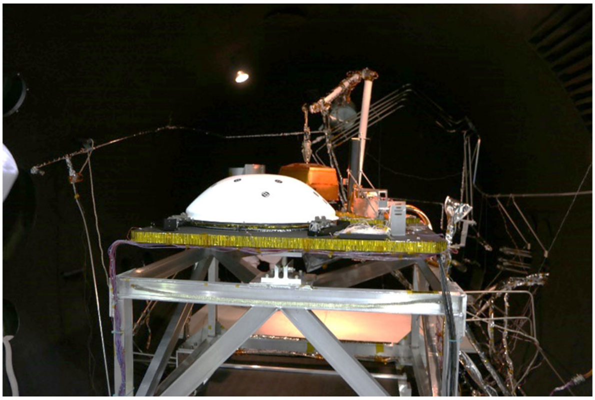


Fig. 3 IDS subsystem setup in a thirteen foot Sensor Chamber at the Raytheon El Segundo Integrated Test Laboratory (ITL), California for thermal characterization test

load shaft. Each joint is equipped with two mechanical hardstops at the end of their range of travel. The encoder counters are initialized based on potentiometer data or by running each joint up against their respective mechanical hardstops.

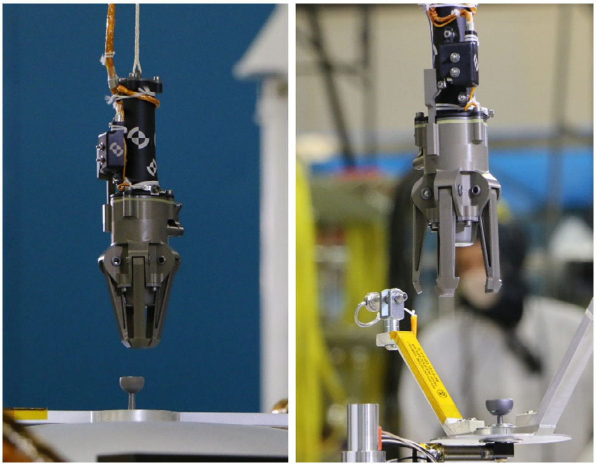
The IDA end-effector consists of a five finger "claw" grapple hanging on an umbilical cable, a scoop, and forearm mounted camera IDC (closer to the elbow joint) facing the IDA end-effector.

Two thermal characterization tests were performed on the IDS subsystem in a thirteen foot Sensor Chamber at the Raytheon El Segundo Integrated Test Laboratory (ITL), California (shown Fig. 3). During the test the IDA heaters were characterized and IDA functional qualification was successfully performed at proto-flight operational temperature. In addition, IDA stop-and-hold torques were characterized at various temperatures.

2.2 IDA End-Effector Grapple

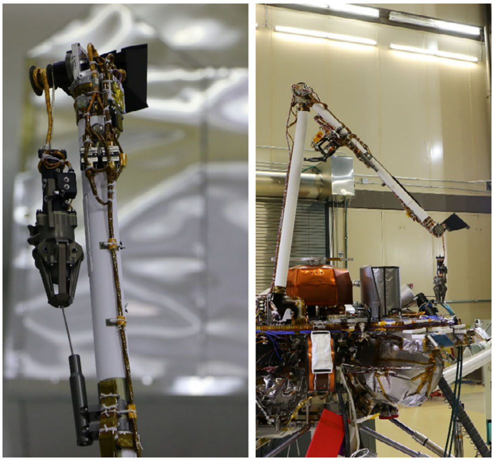
The grapple is a five finger "claw" and hangs by an umbilical at the IDA end-effector. The grapple is designed with five fingers to assure proper self-alignment and be position error tolerant while closing the grapple fingers around the spherical cap grapple hooks on the payloads. The grapple fingers are forced closed. The grapple fingers are opened by a single high output paraffin (HOP) actuator that slowly heats up, melts the wax that pushes a rod out to open the fingers. When the fingers are fully open (as shown in Fig. 4), a limit contact switch trips and turns the grapple HOP heater power off. As the grapple HOP cools down in the ambient temperature, the grapple fingers slowly close passively without any actuation. The grapple design is robust against unexpected power loss because power is required to open the fingers. The grapple umbilical provides the necessary compliance (unactuated additional 2 DOF for the 4 DOF IDA) for engaging and deploying the payloads on tilted Lander and uneven terrain. The grapple is stowed against the IDA forearm such that it does not obstruct the IDC FOV (shown in Fig. 5a). However, when the grapple is unstowed (shown in Fig. 5b) it hangs in the FOV of the IDC such that the IDC images can capture the opening of grapple fingers and engagement of spherical cap grapple hooks on the payload.

During deployment the grapple is unstowed, hanging from the IDA end-effector by an umbilical cable. The IDA can position the grapple to capture the payload's spherical cap grapple hook, lift, and place SEIS, WTS and HP^3 on the Martian surface. The grapple can be stowed using the IDA in a "ball-and-cup" maneuver to the grapple restraint mechanism on the IDA forearm (shown in Fig. 5a).



a b

Fig. 4 Flight Grapple (**a**) fingers closed and (**b**) fingers opened



a b

Fig. 5 (**a**) Stowed Flight Grapple and (**b**) Grapple unstowed from grapple pre-deployment restraint

2.3 IDA End-Effector Scoop

The scoop consists of a single chamber with a front blade and a secondary blade on the bottom side (as shown in Fig. 6). The scoop's front and secondary blades can be used to excavate materials (by digging or scraping) and collect materials excavated in the IDA workspace. The scoop will enable soil mechanics experiments for inferring mechanical properties of the Martian soil at the landing site using the IDA housekeeping data (motor currents, scoop position, etc.) to estimate the scoop's applied force. The scoop is not required for nominal instrument deployment operations.

2.4 IDA End-Effector IDC and Lander ICC

The IDA is used to point the IDC (shown in Fig. 7) to take images of the surface, Lander (selfie), Lander elements, samples in the scoop, 360 degree panorama of the landing site

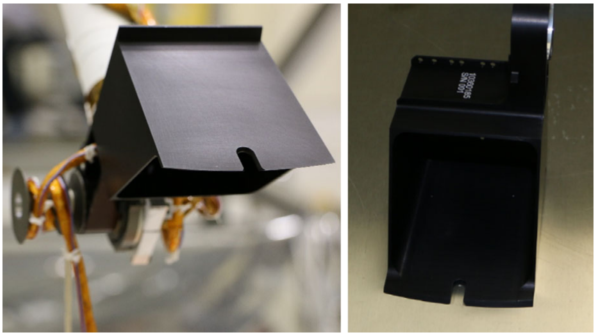

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Fig. 6 (**a**) InSight Scoop mounted on the IDA and (**b**) front view of the scoop before installation on the IDA

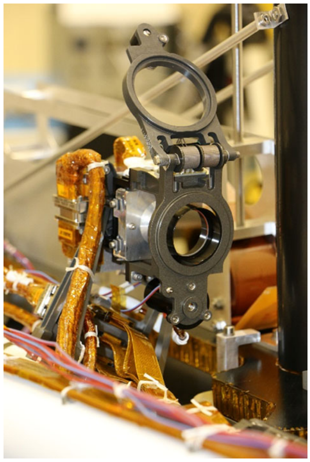


Fig. 7 IDC with dust cover opened

and other geological features at the Landing site. The IDC allows visual confirmation of deployment steps, as well as acquisition of the stereo image pairs used to create a 3D terrain map of the workspace. The IDC also provides engineering images of solar arrays, payload deck, and instruments. The ICC is a single eye camera mounted underneath the Lander (fixed to the Lander) and provides redundant context images of the IDA workspace, horizon and atmospheric optical depth (tau) (Spiga et al. 2018). For more technical details on the InSight color cameras refer to Maki et al. (2018).

InSight will be the first planetary mission to use a single camera and a robotic arm as the primary means to acquire stereo images to generate the DEM of the IDA workspace. Previous Mars surface missions (Mars Pathfinder, Mars Exploration Rovers, Phoenix Mars Lander, and Mars Science Laboratory) carried fixed-baseline stereo mastheads for stereo image acquisition. However, InSight utilizes the heritage flight software and hardware design of Phoenix, which used a Robotic Arm Camera for acquiring images of the end-effector. The IDC and ICC are both Mars Science Laboratory flight spares (Maki et al. 2018). The DEM accuracy requirements were verified in ATLO (Maki et al. 2018).

2.5 IDA Motor Controller

The IDA motor controller consists of two printed-circuit boards located in the lower Payload Electronics Box (PEB) and provides power conditioning, motor voltage control and drivers, grapple heater drivers, joint encoder counting, and analog-to-digital conversion of potentiometer voltages, temperature sensor voltages, motor currents, and heater current. The PEB provides the interface to the Lander Command and Data Handling (C&DH) computer over a serial link. Firmware running on the IDA motor controller microprocessor provides for low-level motor command execution to move the joints to the specified positions, grapple heater command execution, analog-to-digital calibration, and sensor monitoring.

2.6 IDA Flight Software

The IDA flight software (FSW) provides both control of, and visibility into, the IDA hardware. It runs on-board the C&DH computer and communicates with the PEB. IDA FSW provides an interface for IDS ground operators to command the IDA through the PEB. It also sends telemetry data to ground operators, informing them of the current and historical state of both the IDA hardware and software. The IDA FSW inherits from and builds upon the Phoenix Robotic Arm FSW (Bonitz et al. 2008). The IDA FSW provides the following specific capabilities:

- interface with external entities, including other spacecraft FSW components and the IDA PEB
- expansion of high-level IDA commands from the command sequencer into low-level IDA actions
- motion control of the IDA
- control of the grapple
- fault sensing, recovery, and safing
- collision prevention between the IDA, lander, and science instruments
- visibility of the IDS state in telemetry.

The IDA FSW responds to sequences of IDA commands, where the sequences are similar to scripts in a domain-specific high-level scripting language. The IDA FSW handles commands from the sequence engine one at a time, taking action as appropriate. To handle each command, the IDA FSW may communicate with the PEB, reading and writing to a virtual device, or send commands to power-switching FSW.

Most IDA movement commands specify a single movement, although some are more complicated, such as higher-level commands to calibrate the motors, dig a trench, or scrape the Martian surface. IDA commands which specify movement can specify the desired movement in terms of the goal joint angles, a Cartesian position and approach angle for the specified tool, or a direction and length of time to move certain motors. Goal positions, either Cartesian or joint angles, can be absolute positions or relative to the current position.

Together, the IDA FSW and the motor controller in the PEB provide for stable motion control of the robotic arm. IDA FSW breaks motion commands down into a sequence of via points describing intermediate joint positions to achieve the desired motion. IDA FSW issues motor commands to the PEB for each via point, sending a new via point once the arm reaches the current one. The IDA FSW provides the command decomposition into via points, trajectory generation for each via point, and fault monitoring. The motor controller in the PEB provides low-level motor command execution to move the joints to the specified angles in the via points.

Coordinated joint motion is achieved by a trapezoidal trajectory profiler and proportional-integral-derivative (PID) controller. The trapezoidal trajectory profiler computes the velocity profile for each joint at the beginning of each via point to achieve coordinated motion. The trapezoidal profile provides for smooth joint startup and ramp down and a running velocity that assures all joints complete their motion simultaneously. The PID controller computes the motor voltage for each joint to follow its trapezoidal velocity profile in real-time and sends the voltage values to the motor controller in the PEB. To achieve smooth motion from one via point to another, IDA FSW sends the motor commands for the next via point just prior to achieving the current via point (Bonitz et al. 2008).

During arm motion, both the IDA FSW and PEB monitor motor currents to prevent excessive joint torques from damaging the joints. Additionally, the IDA FSW monitors joint positions from the encoders and potentiometers, joint torques from the current, joint and grapple temperatures, and joint and grapple heater current. Using current and historical values of this data, the IDA FSW detects any unrecoverable faults or recoverable events that may have occurred. If it detects any problem, the standard IDA FSW response is to safe itself, or “stop and wait”. This involves stopping arm motion, powering off the PEB, and marking itself failed, which prevents further non-recovery IDA commands from executing. Then, it waits for ground operators to review the problem and send recovery commands. For certain recoverable events, IDA FSW may autonomously attempt to recover from the condition. If the autonomous recovery attempts fail, the IDA FSW executes the “stop and wait” response.

The IDA kinematics describe the geometrical relationships among the IDA elements. The forward kinematics maps IDA joint angles to the pose of the selected tool in Cartesian space. The inverse kinematics maps the pose of the tool to the corresponding joint angles. IDA FSW computes the forward and inverse kinematics to enable and determine IDA placement. Since the grapple hangs in the direction of gravity, when the grapple is in use, the forward and inverse kinematics computation also uses the relative direction of gravity in the IDA base frame.

Due to the stiffness and mass of the IDA, the links can deflect under their own weight and the weight of a grappled payload. The IDA FSW computes the expected deflection from an internal model of the IDA stiffness and mass properties, knowledge of the grappled science instrument payload, payload masses, and the relative direction and magnitude of gravity. It then compensates for the computed deflection.

For motion commands, the IDA FSW checks each computed via point for potential collisions between the IDA, any grappled payload, the lander, and non-grappled payloads. The collision checking software uses geometric models of the IDA, lander, and payloads. The poses of objects attached to moving parts are determined prior to the collision check, based on the forward kinematics.

To open the grapple, the IDA FSW runs a high output paraffin (HOP) actuator, causing the wax to push open the grapple fingers. Care must be taken, because if the wax gets too hot, the grapple actuator will be damaged. IDA FSW monitors the limit switches which indicate if the fingers are open, to determine when to turn off the heater. It also monitors the actuator temperature and the duration the actuator is powered, powering the heater off if necessary to prevent damage. There is no command to close the grapple. When the HOP actuator is not powered, a spring pushing against the contracting wax slowly forces the fingers closed.

3 IDS Operations

3.1 Deployment Workspace

Figure 8 shows a top view of the deployment workspaces for SEIS and WTS. The coordinates are specified in the IDA frame as the reference frame to be used for surface operations

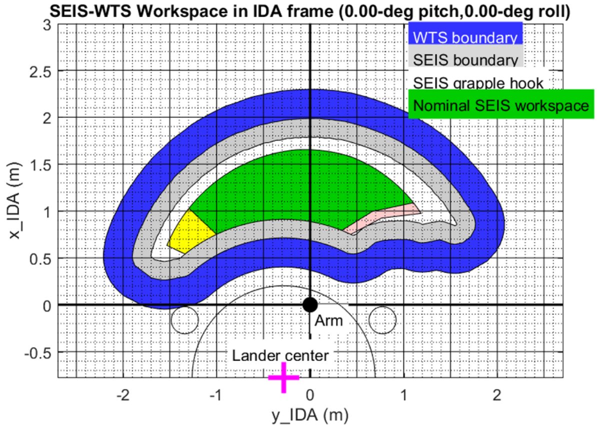


Fig. 8 SEIS-WTS deployment workspaces for level lander with level surface in IDA frame coordinates. The green zone is the nominal IDA grapple workspace for SEIS and WTS deployments. Its outer boundary's radial distance from the arm base is 1.65 m. In the yellow zone, ICC view partially occluded. In the pink zone, WTS deployment at higher height over SEIS requires more maneuvering to handle collision prevention

on Mars. The IDA frame origin is at the IDA arm base, fixed on the lander deck with the x-axis towards workspace and the z-axis down perpendicular to the lander deck. The nominal height of the lander deck is 1.05 m with the z-coordinate of the level surface is 1.05 m in IDA frame. In Fig. 8, the lander deck and its nearby footpads touching the surface are represented by circles of 97.8 cm and 14.5 cm radii, respectively. The white area including all inner overlapping regions is the kinematically reachable SEIS/WTS payload grapple hook workspace, where IDA grapple holding the payload grapple hook can reach and perform instrument placement on the level surface with nominal lander deck height. The SEIS/WTS grapple hook workspace is bounded by (1) outer circular boundary constrained by kinematic reachability of the arm for both SEIS and WTS placements, (2) inner circular boundary constrained by collision prevention between WTS (larger than SEIS) and the lander structure, and (3) side boundaries constrained by collision prevention between the arm and the lander deck. The gray area including all inner overlapping regions is the SEIS footprint boundary (19.8-cm radius circle) workspace. The blue area including all inner overlapping regions is the WTS footprint boundary (50.8-cm radius circle) workspace.

The green zone is the nominal IDA grapple workspace for SEIS and WTS deployments. Its outer circular boundary is reduced from the kinematically reachable workspace by several constraints: (1) manipulability avoiding near singularity regions, (2) torque limits, (3) arm joints backdrive (IDA does not have mechanical brakes), (4) SEIS tether length, and (5) payload recapture for relocation contingency. The radius of the outer circular boundary of the green zone resulted in 1.65 m from the arm base. Its side boundaries are confined by the yellow and pink zones. In the yellow zone, the ICC field of view partially occluded. In the pink zone, WTS deployment at higher height over SEIS requires more maneuvering to handle collision prevention.

To minimize the effect of the noise contributions of the lander, scientists prefer to place the SEIS as far away from the lander footpads as possible. One such location is (1.65 m, 0 m) in xy coordinates at the intersection of the outer boundary of the green zone and the x-axis projected on the surface. Another location is (1.59 m, 0.44 m) along the tether peel direction.

Figure 9 shows the deployment workspaces for HP^3. They are very similar to those for the SEIS and WTS deployments above. The blue area including all inner overlapping regions is the HP^3 footprint boundary (31.2-cm radius circle) workspace. Scientists prefer to place HP^3 similarly far away from the lander and greater than 1 m away from SEIS.

Lander tilt has a significant effect on the payload deployment workspaces and must be considered. Figure 10 shows SEIS-WTS workspaces on the IDA frame xy-plane for four

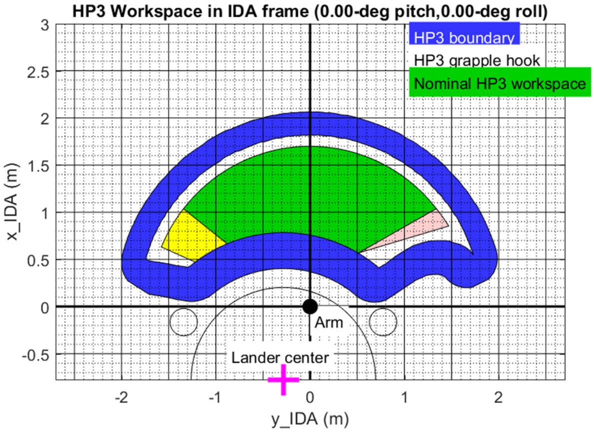


Fig. 9 HP[3] deployment workspaces for level lander with level surface

different lander tilt cases with the lander (IDA frame origin) height of 1.05 m from the level surface and lander footpads. Note that the workspaces and footpads on the surface are moving together, relative to the lander deck boundary. For positive lander pitch of Fig. 10(a), the maximum x-coordinate in IDA frame for the nominal deployment was reduced to 1.45 m while it was 1.65 m for level lander. For negative lander pitch of (b), it increased to 1.8 m, but the positive-y workspace zone shrank due to an arm collision issue. For positive lander roll of (c), the positive-y workspace zone increased while the negative-y workspace zone decreased. For negative lander roll of (d), the opposite trend happened.

Beyond the workspace reachability constraints, successful instrument deployments require knowledge of the 3-D workspace terrain to select the deployment site.

3.2 Workspace Imaging, Terrain Mosaic, and Site Selection

Prior to the instrument deployment, we need to know the workspace terrain in 3-D coordinates. An IDC stereo mosaic is acquired of workspace to create a DEM. In order to minimize stereo baseline error, IDC stereo pairs are acquired by moving one arm joint only—the shoulder joint—while keeping all the other joints constant. The stereo overlap between left and right images is 80% enabling generation of workspace DEM comparable to MER, PHX and MSL missions. IDC images are acquired using the IDA in an event driven mode or a spawn mode. IDC workspace imaging is done in event driven mode with sequence structure to capture images of the robotic arm's workspace in several tiers, starting with an inner tier close to the base of the lander and moving progressively outward. Only the IDA azimuth joint angle is changed within a tier. To move from one tier to the next, IDA elbow joint angle is changed. Stereo pairs of IDC images are obtained by making small moves to the IDA azimuth to accomplish 80% overlap, and include a unique 32 bit label called image I.D. assigned to each image to identify it as a left or right image in the stereo pair (Trebi-Ollennu et al. 2013). The left eye and right eye image data products are used by a ground tool to perform stereo ranging. The range data from each pair of images is combined into a composite point cloud and used to generate a digital elevation map, also called a terrain mesh (see Fig. 11). Additional imaging data products are generated from the IDC stereo mosaic (Abarca et al. 2018).

The Instrument Site Selection Working Group (ISSWG), which consists of science and engineering teams, reviews the workspace DEM and corresponding image products to select suitable sites to place the payloads. The site selection has doublets (one of a pair) for

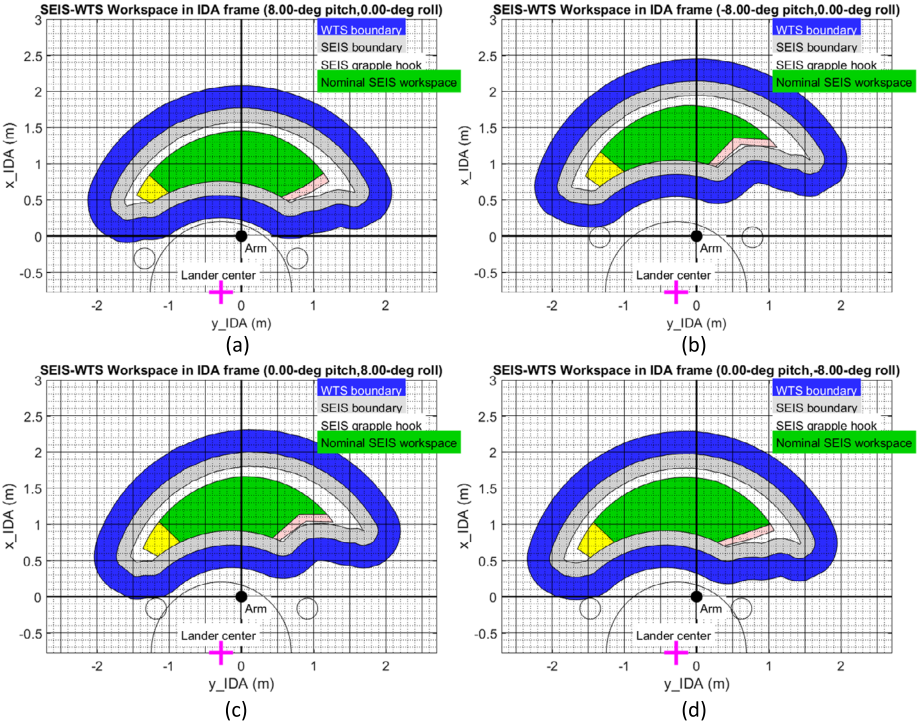


Fig. 10 SEIS-WTS deployment workspaces for tilted lander with level surface. (**a**) 8-deg pitch and 0-deg roll lander (**b**) −8-deg pitch and 0-deg roll lander (**c**) 0-deg pitch and 8-deg roll lander, and (**d**) 0-deg pitch and −8-deg roll lander

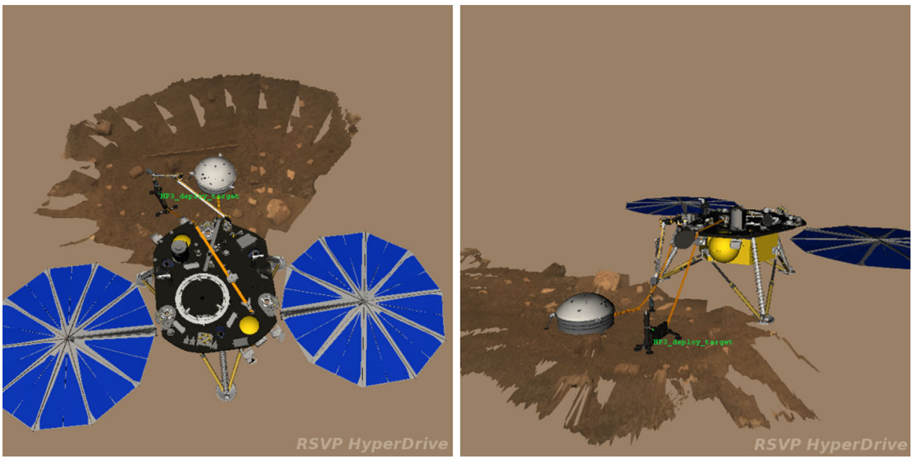
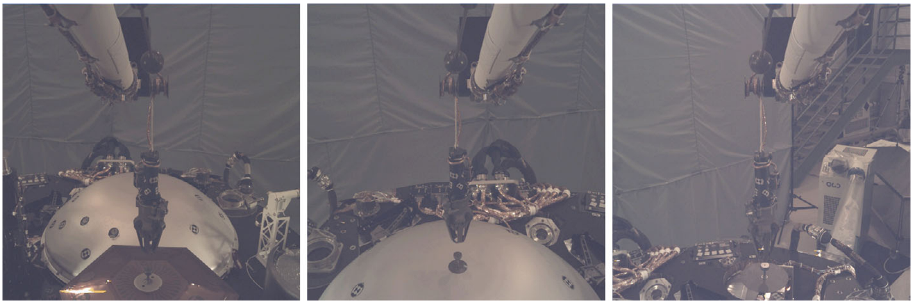


Fig. 11 RSVP Hyperdrive view of workspace terrain mesh generated using 56 IDC images with SEIS, WTS and HP^3 deployed



IDC Image of SEIS Teachpoint | IDC Image of WTS Teachpoint | IDC Image of HP^3 Teachpoint

Fig. 12 Flight Grapple at Flight SEIS, WTS and HP^3 Teach points during ATLO IDS closeout

SEIS/WTS and HP^3 in order to address intra payload placement constraints. An example of intra payload placement constraint is a 1 m distance between HP^3 and WTS in order to minimize WTS casting a shadow over the HP^3 mole penetrating site.

3.3 Payload Deployment Steps

Once the final sites for SEIS/WTS and HP^3 have been selected, the IDS team is responsible for building the sequences to place the payloads in the workspace. The IDS team uses the robot sequencing and visualization program (RSVP) (Yen et al. 2004) for building and simulating sequences (shown in Fig. 11). RSVP provides high-fidelity 3-D modeling of the IDA, lander, instruments, workspace terrain (DEM), and detailed simulations of IDA motion, which is driven by the ground version of the IDA flight software, including collision prevention, and outputs a complete command sequence file for uplink to the Lander. RSVP has been used on Pathfinder, Mars Exploration Rovers, Phoenix Mars Lander, and Mars Science Laboratory projects.

For each of the deployable payloads a standard "teach repeat" (teach points) technique was used to learn a point 4 cm above their grapple hook position on the Lander deck. This was accomplished by positioning the grapple over their respective grapple hook position and moving the grapple 4 cm above the payload grapple hook. The absolute position of the grapple at the position was recorded in Cartesian frame as the payload teach point. Although, these teach points were in Earth gravity on Mars the IDA-FSW will compensate for the difference in gravity and Lander tilt using the IDA deflected kinematics to adjust the teach points. The teach points takes advantage of the excellent IDA repeatability performance of 5 mm.

Each payload deployment (lift from the Lander deck to placement on surface) consists of four parts (Part 1, Part 2, Part 3, and Part 4). After completion of each part there is a ground-in-the-loop GO/NO GO decision to execute the following part.

Part 1 of each payload deployment entails moving the unstowed grapple to the corresponding payload teach point. The payload teach points are 5 cm above the grapple hook position of the payload as stowed on the Lander deck (shown in Fig. 12). At the payload teach point four IDC images are acquired for the ground operators to confirm proper alignment needed for the GO/NO GO decision for Part 2.

Part 2 consists of opening the grapple fingers and moving the fully open grapple fingers 4 cm down to capture the payload as shown in Fig. 4b. During the opening of the grapple fin-

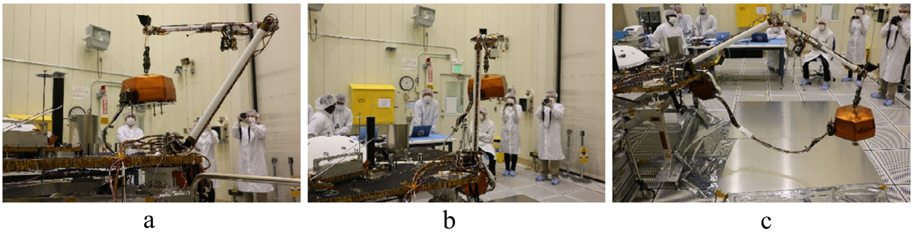


Fig. 13 SEIS Weight Model Part 3 Deployment Steps

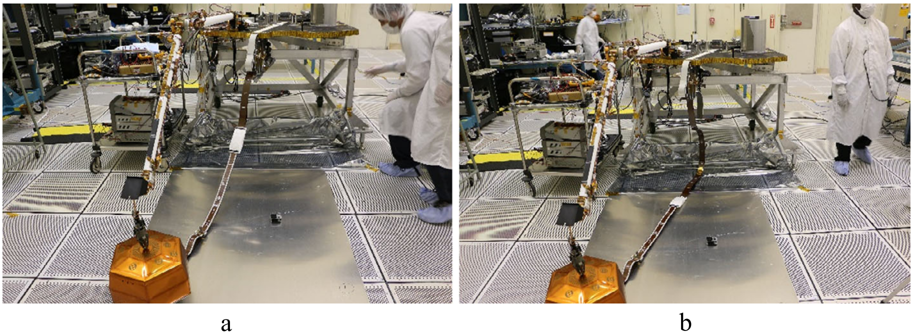


Fig. 14 (a) Pre-TSB Door Open and (b) Post-TSB Door to release remaining SEIS tether in TSB

gers and IDA motion to capture the payload, multiple IDC images are acquired to document operations and are used as decisional data for the Go/NO GO to proceed to Part 3.

Prior to executing Part 3 the payload is released from its launch restraint by actuating the restraints frangibolts. Multiple IDC images are acquired to document operations and are used as decisional data for the GO/NO GO to proceed to Part 4. Part 3 entails lifting the captured payload and placing it in the IDA deployment workspace (surface of Mars).

A 3 m long, and 4.5 cm wide tether connects the SEIS sensor head assembly on the Lander deck to the SEIS electronics box in the Lander thermal enclosure. Approximately 2 m of the SEIS tether is stored in the Tether Storage Box (TSB) underneath the front of the Lander and the remaining tether is mounted to the Lander deck and TSB ramp by Velcro (as shown in Fig. 13a to 13c). SEIS tether management is accomplished with a chock mounted on the SEIS tether such that the IDA can only extract up to the maximum SEIS tether length required to place the SEIS at the maximum distance from the Lander.

SEIS deployment Part 3 consists of an initial 30 cm lift of SEIS from the SEIS launch restraint pedal stools, followed by peeling the SEIS tether held on the Lander deck and the Tether Storage Box (TSB) ramp as shown in Fig. 13a to 13c.

After peeling the SEIS tether from the Lander deck and TSB ramp the IDA moves the SEIS to a known pose far out in the workspace to extract additional SEIS tether from the TSB up to the SEIS tether chock. The IDA then moves and places SEIS on the surface. Post SEIS placement on the surface the SEIS science operations team perform SEIS health checkouts and then the remaining SEIS tether in the TSB is released by opening the TSB door as shown in Fig. 14.

An intra-SEIS payload constraint requires successful verification of separation of the SEIS load shunt assembly (LSA) mechanism before proceeding with WTS deployment.

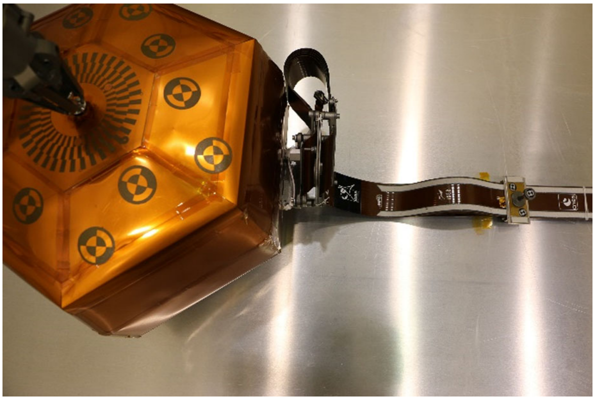


Fig. 15 SEIS Tether with LSA Service Loop and Pinning Mass

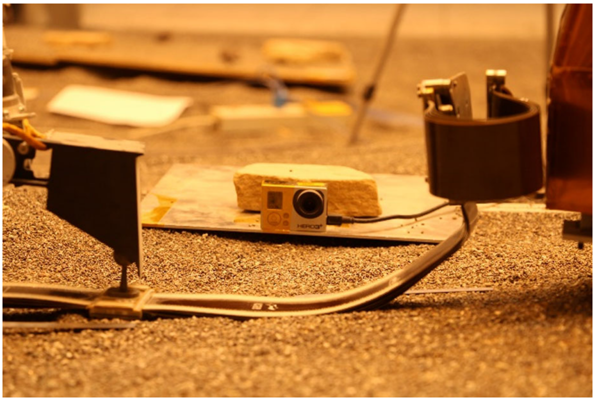


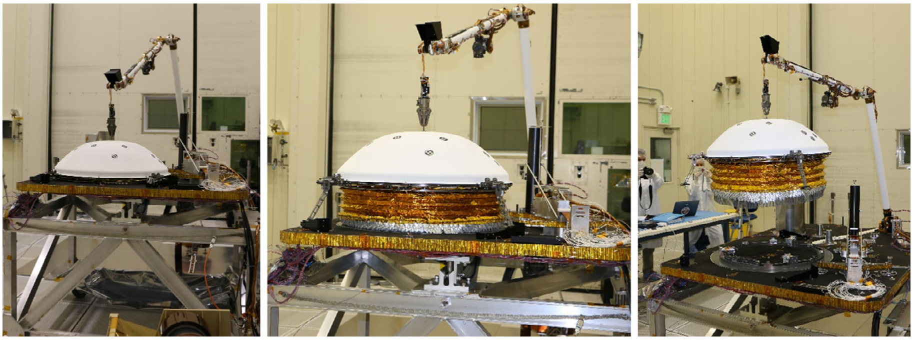
Fig. 16 IDA Scoop moving the PM via the PM grapple hook to separate the LSA

To dampen the effects of tether thermoelastic noise on the seismic measurements, the SEIS sensor head is connected to the SEIS tether via a service loop and a load shunt assembly (LSA) mechanism (as show in Fig. 15). In addition, the SEIS tether is grounded to the surface with a pinning mass (PM) (as show in Fig. 16) mounted to the tether.

A successful separation of the LSA is required for SEIS to meet its performance requirements. If successful actuation of the LSA frangibolt does not result in meeting the minimum LSA separation distance, the IDA scoop will be used to move the PM via the grapple hook to assure successful LSA separation (as shown in Fig. 16).

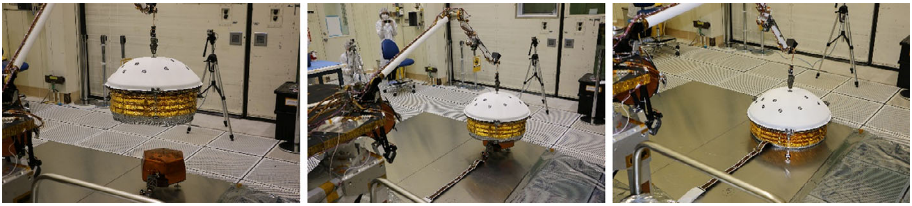
The WTS is free standing on the Lander deck, that is, it is not tethered to the Lander. WTS deployment Part 3 post launch restraint release consists of an 18 cm lift off the Lander deck to a stand up pose to enable the three folded WTS legs to deploy and the release of the WTS skirt as shown in Fig. 17. There is no ground in the loop confirmation of successful WTS legs deployment. Post WTS stand up, the WTS is lifted an addition 43 cm off the Lander deck and moved around the IDA minus y axis side of the Lander to the deployment workspace in front of the Lander as shown in Fig. 18. The WTS is then placed over the SEIS with at least a 5 cm offset towards the IDA base from the center (SEIS grapple hook) of SEIS.

The HP^3 support structure and sensor head has two tethers, a 4 m engineering tether (ET) that is connected to the HP^3 electronics box in the Lander thermal enclosure. The second



a b c

Fig. 17 Photos of WTS Weight Model (**a**) WTS Capture, (**b**) WTS stand up—legs and skirt deployed and (**c**) WTS lifted above the Lander Deck



a b c

Fig. 18 Photos of WTS Weight Model (**a**) WTS at first standoff distance over SEIS, (**b**) WTS at second standoff distance over SEIS and (**c**) WTS placed over SEIS

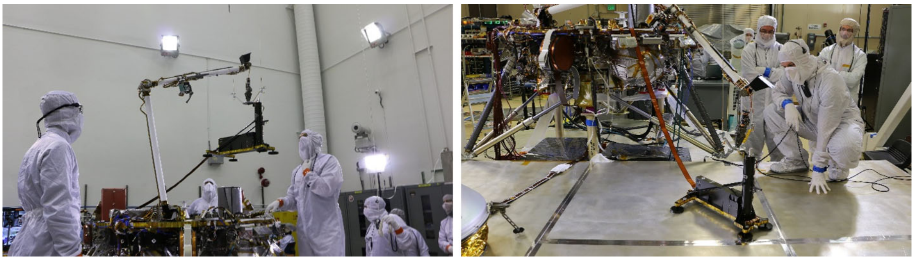


Fig. 19 Photos of flight HP^3 Deployment (**a**) HP^3 lifted above the Lander deck and (**b**) HP^3 placed in the deployment workspace

HP^3 tether is a science tether connected to the heat probe directly. Both HP^3 ET and science tether are stored in the HP^3 support structure.

HP^3 deployment Part 3 consists of lifting the HP^3 40 cm above the Lander deck post launch restraint release. During the IDA lift of HP^3 the HP^3 ET is extracted from the HP^3 support structure as shown in Fig. 19. Subsequent IDA moves extracts the HP^3 ET tether across the Lander deck and places the HP^3 in the designated deployment workspace site in front of the Lander. Post placement of HP^3 in the deployment workspace a series of HP^3 health checks are performed by the HP^3 science operations team.

Fig. 20 SEIS Weight Model Deployment Part 4 release steps

Payload deployment Part 4 is called payload release, and it consists of opening the grapple and moving the IDA up and away from the payload grapple hook as shown in Fig. 20.

After each payload deployment, we will perform payload grapple localization. By determining the position and orientation of each deployed payload on the surface, we will demonstrate the ability to return to a point 1 cm above the grapple hook of each instrument in the event a recapture is required. This analysis occurs on the ground with a combination of images of the payloads, fiducial localization, and stereo range data (see Sect. 3.4). The surface operations activity requires moving the IDA in free space to the computed point above the payload and taking an IDC image to confirm location. If the science team determines that the deployment location is unsatisfactory after deployment, IDS can recapture the payload and move it to a different location in the workspace.

The above outlined operational sequences were developed during a series of subsystem and system level test campaigns in Phases B, C and D of the project. During the IDS thermal characterization test, Mars weight models of each of the deployable items were successfully deployed at cold temperature, −35 °C and −50 °C (SEIS and WTS only).

No gravity offloading was implemented for the IDS thermal characterization tests. The SEIS and HP^3 weight models included their respective flight like tethers.

In addition, during InSight 2017 Assembly Launch Test Operations (ATLO), Deployment Scenario Test at Lockheed Martin, Denver. The flight SEIS, WTS and HP^3 were successfully deployed by IDS using flight sequences at ambient (~ 20 °C) temperature with a balloon gravity offload fixture to compensate for Mars to Earth gravity.

Additional payload deployment Verification and Validation tests continue at JPL using Spacecraft Test Laboratory 3 (STL3) which is equipped with weight models of SEIS (including tether), WTS, HP^3 (including engineering tether), engineering models of the ICC, IDC, PEB, Lander mock with 3D printed deck components, flight software (FSW) and engineering model of the spacecraft C&DH. STL3 enables the IDS team to perform deployment test at various combinations of Lander tilts and workspace slopes. The IDS team will also use STL3 to dry-run flight sequences.

3.4 Payload Localization in Deployment Workspace

Each of the payloads have fiducials mounted on the exterior of their support structure as shown in Fig. 21. The SEIS and WTS use fiducials from Mars Curiosity rover and HP^3 uses a combination of Mars Curiosity rover fiducials and AprilTags (Olson 2011; Wang and Olson 2016). Each Curiosity rover fiducial represents a single known reference point while each AprilTag represents five points along with a unique rotationally non-symmetric pattern that encodes its orientation. The relative position of each marker was measured precisely on Earth so the position and orientation of each payload can be reconstructed by a ground operator from a single monocular image.

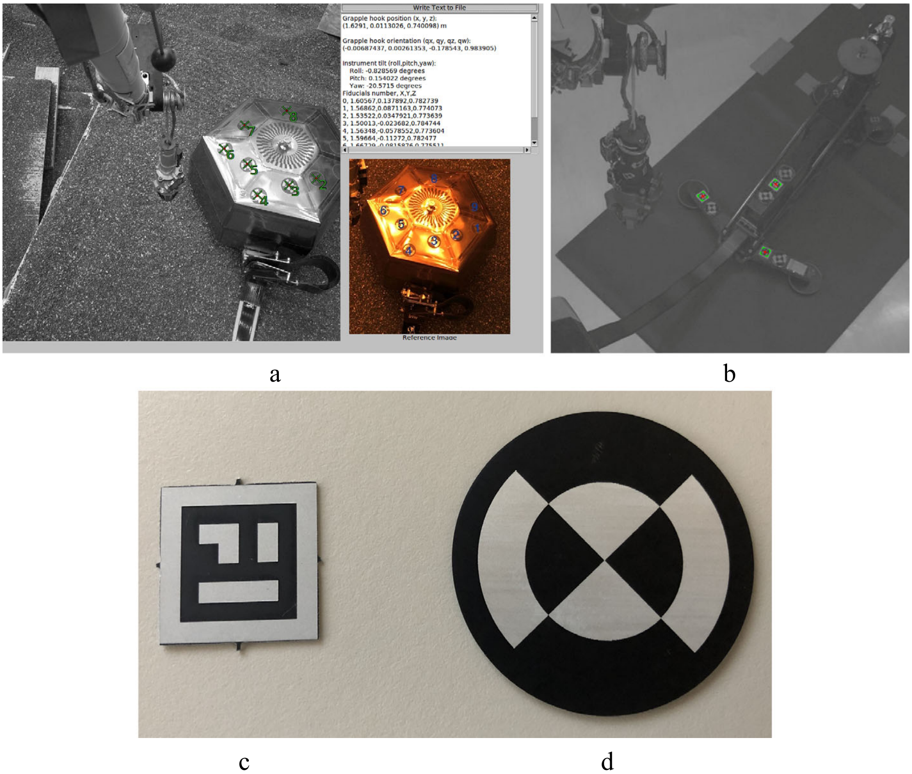


Fig. 21 IDC Images of Weight Model SEIS (**a**), Flight HP^3 (**b**) with fiducials detection ellipse, (**c**) AprilTag, and (**d**) MSL Fiducial

3.5 IDS Soil Mechanics Capabilities

The InSight IDA retains a subset of the Phoenix Robotic Arm Icy soil acquisition capabilities (Bonitz et al. 2008) such as blade scraping and limited dig trench functionality using a single command. In addition, the IDA provides guarded motion capability similar to the Phoenix robotic arm, a single command that allows the IDA to be commanded to move to a position until contact is made. This is accomplished by monitoring motor currents and computed joint torques versus preset thresholds. On InSight, guarded move command capability will enable IDA physical properties experiments enumerated in Golombek et al. (2018) such as indentation, collapse of trench walls, and scraped and excavated dump piles.

4 Conclusions and Summary

In this paper, we have presented extensive details of subsystem and system level integration and test conducted for verification and validation of the InSight Mars Lander, Instrument Deployment Systems (IDS). IDS is responsible for the first robotics precision instrument placement and release (seismometer and heat flow probe instruments) on a planetary surface that will enable scientists to perform the first comprehensive surface-based geophysical investigation of Mars. The successful early subsystem and system level test campaigns have led to the development of a very mature and robust detailed surface operations steps for the deployment of SEIS, WTS and HP^3 pre-launch. This is unprecedented for a Mars surface mission to have completed detailed surface operations campaign in pre-launch phase of the mission. The IDS is ready for launch and Mars surface operations.

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References

H. Abarca et al., Image and data processing for InSight lander operations and science. Space Sci. Rev. (2018, this issue)

W.B. Banerdt et al., The InSight mission. Space Sci. Rev. (2018, this issue)

R.G. Bonitz, T.T. Nguyen, W.S. Kim, The Mars Surveyor '01 Rover and Robotic Arm, in *IEEE Aerospace Conference, Proceedings (Cat. No. 00TH8484)*, vol. 7 (2000), pp. 235–246

R.G. Bonitz et al., NASA Mars 2007 Phoenix lander robotic arm and icy soil acquisition device. J. Geophys. Res. **113**, E00A01 (2008). https://doi.org/10.1029/2007JE003030

W. Folkner et al., The rotation and interior structure experiment on the InSight mission to Mars. Space Sci. Rev. (2018 this issue). https://doi.org/10.1007/s11214-018-0530-5.

M. Golombek et al., Geology and physical properties investigations by the InSight lander. Space Sci. Rev. (2018, this issue). https://doi.org/10.1007/s11214-018-0512-7

P. Lognonné et al., SEIS, SEIS: the seismic experiment for internal structure of InSight. Space Sci. Rev. (2018, this issue)

J.N. Maki et al., The Mars InSight lander cameras. Space Sci. Rev. (2018, this issue)

E. Olson, AprilTag: a robust and flexible visual fiducial system, in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)* (IEEE, Los Alamitos, 2011), pp. 3400–3407

A. Spiga et al., Atmospheric science with InSight. Space Sci. Rev. (2018, this issue)

T. Spohn, M. Grott et al., The heat flow and physical properties package (HP^3) for the InSight mission. Space Sci. Rev. (2018 this issue). https://doi.org/10.1007/s11214-018-0531-4.

A. Trebi-Ollennu, A.L. Rankin, C. Yang, K.S. Tso, R.G. Deen, H. Aghazarian, E.A. Kulczycki, R.G. Bonitz, L. Alkalai, Instrument deployment testbed: for planetary surface geophysical exploration, in *Aerospace Conference*, 2–9 March, 2013 (IEEE, Los Alamitos, 2013)

J. Wang, E. Olson, AprilTag 2: efficient and robust fiducial detection, in *Proceedings of the International Conference on Intelligent Robots and Systems (IROS)* (IEEE/RSJ, Daejeon, 2016), pp. 4193–4198

J. Yen, B. Cooper, F. Hartman, S. Maxwell, J. Wright, Sequence rehearsal and validation on surface operations of the Mars exploration rovers, in *Proceedings of SpaceOps 2004*, Montreal, Canada (2004)