# INSIGHT INSTRUMENT DEPLOYMENT ARM

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## ABSTRACT

The Mars InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) Program will utilize a special lightweight robotic arm termed the Instrument Deployment Arm (IDA). This paper will focus on the mechanical implementation of the IDA.

The IDA originated as the robotic arm built for the Jet Propulsion Laboratory (JPL) for the cancelled Mars 2001 Surveyor mission in 1998. The IDA is slated for refurbishment, followed by subsystem testing of its actuators, and then system testing of the full arm.

This paper will delve into the specifics of the IDA electro-mechanical design, which includes light-weight actuators, multi-conductor flex-print cable, and a self-triggered launch-restraint system. The history of the design, which draws from elements as far back as the Mars Pathfinder Sojourner rover, will be discussed.

Also discussed will be the specifics of the refurbishment, decisions made governing the level of refurbishment enacted, and planned post-refurbishment testing.

## 1. INSIGHT MISSION

The Mars InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) mission is slated to launch in March of 2016. The program will utilize a special lightweight robotic arm, termed the Instrument Deployment Arm (IDA), to deploy two scientific instruments: the Seismic Experiment for Interior Structure (SEIS), provided by the French Space Agency (CNES), with the participation of the Institut de Physique du Globe de Paris (IPGP), the Swiss Federal Institute of Technology (ETH), the Max Planck Institute for Solar System Research (MPS), Imperial College and the Jet Propulsion Laboratory (JPL); and the Heat Flow and Physical Properties Package (HP3), provided by the German Space Agency (DLR). The IDA will reside on the upper deck of the InSight Lander, which is very similar to the Lockheed-built lander used for the Phoenix mission which landed in on Mars in May 2008.

Two main goals of the mission are to understand the formation and evolution of terrestrial planets through investigation of the interior structure and processes of Mars; and to determine the present level of tectonic activity and meteorite impact rate on Mars. Fig. 1 shows an artist's illustration of the lander on Mars with the IDA extended and the SEIS and HP3 deployed on the Martian surface [1].

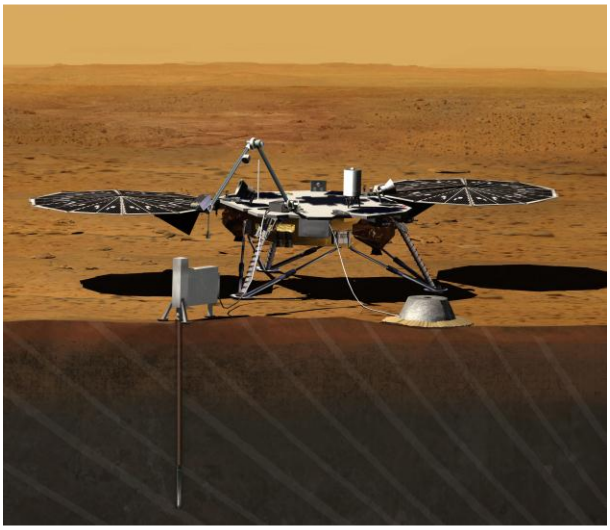

*Figure 1. InSight lander with IDA deployed.*
*[image credit JPL/NASA]*

## 2. INSTRUMENT DEPLOYMENT ARM (IDA)

### 2.1. History

The IDA is an extremely lightweight robotic arm capable of generating high joint torques in order to lift and manipulate payloads. The IDA is essentially the same design as the robotic arm that assisted the MVACS experiment sent to Mars in 1998 as part of the Mars Polar Lander (MPL) mission [2]. Following this, the MPL robotic arm design was essentially rebuilt for the Mars 2001 Surveyor mission by MDA US Systems, LLC in 1998—then known as Alliance Spacesystems, Inc—albeit with a few design differences. Shortly following delivery of the Surveyor arm to the JPL in 1999 for further system-level testing (primarily thermal-vacuum and vibration testing), the Surveyor mission was cancelled. As a result, the Surveyor arm was put into storage in a shipping container with an elastomeric edge seal and a standard atmosphere. For the InSight mission, the Surveyor arm has been "resurrected" to serve as the IDA and re-purposed for the new mission. The IDA is currently being refurbished for testing of its actuators followed by testing of the fully assembled arm. Because the progenitor MPL arm design is about 15 years old, and the follow-up Surveyor arm is about 13 years old, refurbishment, testing, and subsequent

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flight of the IDA is an unusual and interesting occurrence. One aspect of this is that the software used to design both arms did not at the time have reliable solid modeling capability; rather, all electronic representations of the IDA were constructed using 2D and 3D wire-frame techniques with software that hasn't been in-use at JPL or MDA US Systems, LLC for over a decade.

### 2.2. IDA Design

The IDA was first and foremost designed to be extremely lightweight and the philosophy during its development was verification through testing rather than extensive analysis. This was especially true because the more primitive FEM techniques at the time were at-odds with the IDA's complicated, lightweight part-shapes, load paths through multiple linked joint actuator mechanisms, and complex topology overall. The mass of the IDA is approximately 3.4 kg without payload and end-effector. It is comprised of 4 actuators, interconnecting structure, multiple layers of flex-print with about 130 conductors, and a self-actuated ("bootstrapped") launch restraint system. Fig. 2 shows the IDA major subcomponent nomenclature.

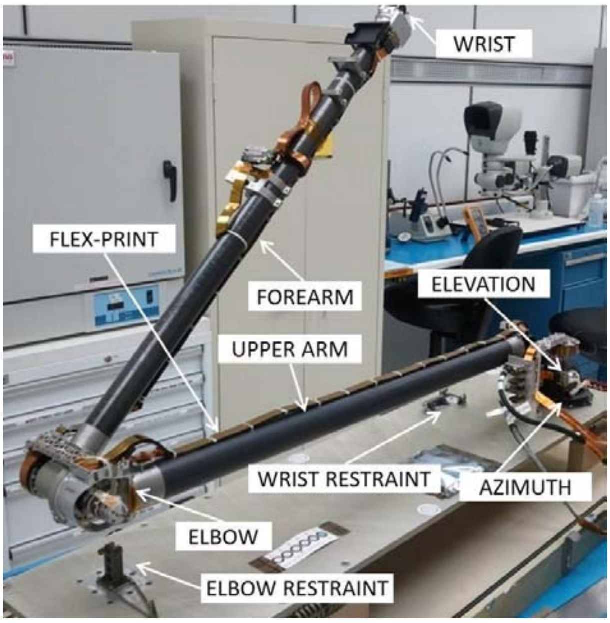


*Figure 2. InSight IDA subcomponent nomenclature*

#### 2.2.1. Actuators

The IDA is a 4-degree of freedom (4-DOF) manipulator with a motorized joint actuator for each DOF. The actuators as numbered from the base-mount of the IDA from 1 to 4 and are named as follows:

1. Shoulder Azimuth
2. Shoulder Elevation
3. Elbow
4. Wrist

Actuators 1-3 share a common architecture of motor/planetary gearbox/harmonic gear/output bearing. Actuator 4 differs in that the harmonic gear is replaced by a bevel gear pair. Fig 3. shows each actuator (actuators 1 and 2 share a common housing) and Table 1 highlights primary design characteristics and performance parameters derived from testing of the Mars Surveyor arm.

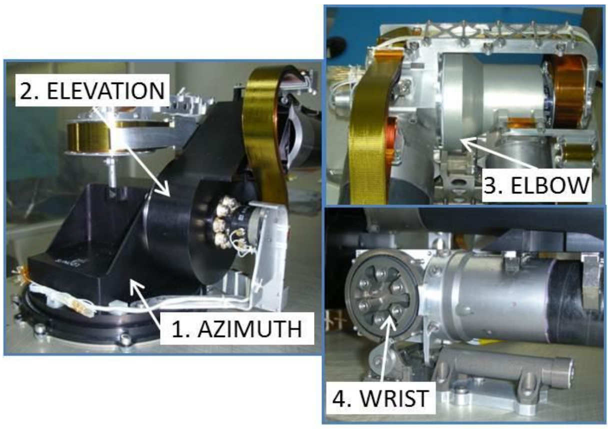


*Figure 3. InSight IDA actuators*

All actuators are driven by ATC motors with graphite brushes. These motors were selected following a period of testing in Martian atmospheric conditions [3]. At the time of selection, brushed motors were preferred over brushless motors due to electrical simplicity and a history of usage at JPL, most notably on the Mars Pathfinder mission and its Sojourner rover. As a side-note, similar brushed motors were used once again for the 2003 MER and 2008 Phoenix missions. The motors are equipped with redundant thin-film heaters and a single bonded-on platinum resistance thermometer (PRT). The motors have iron core rotors with naturally occurring detent torque that provides joint-holding torque when the actuators are powered off.

Planetary gearing is constructed from modified commercial gear components from Globe Motors (replacement parts are not currently manufactured). Ring-gear cross-sections and individual gear face-widths have been machined to be thinner to save mass and reduce overall actuator length. Planetary stages 1 and 2 in actuators 1-3 incorporate small ball bearings; planetary stages 1, 2, and 3 in actuator 4 incorporate similar ball bearings. Other stages use bushings and posts. Bearings are chosen for high efficiency in the low-torque section of the gearboxes, and bushings are used when gearbox torque transitions to higher levels.

Output from the planetary gearing is used to drive a cup-type harmonic gear component-set in the case of joints 1-3, and a bevel gear pair made of Vascomax C300 for joint 4. Harmonic gearing is made of standard commercial materials and the bevel gear set is custom fabricated.

Table 1. IDA Actuator Parameters

| | Shoulder Azimuth | Shoulder Elevation | Elbow | Wrist |
|---|---|---|---|---|
| Planetary Ratio [n:1] | 125 | 100 | 100 | 2,000 |
| Planetary Stages | 3 | 3 | 3 | 5 |
| Harm/Bevel Ratio [n:1] | 100 | 160 | 100 | 2 |
| Range of Motion [deg] | 284 | 215 | 285 | 215* |
| Max T @28V [Nm] | 47 | 148 | 87 | 15 |
| Speed @ Max T [rpm] | 0.32 | 0.25 | 0.40 | 1.00 |
| I, No-load @ 23ºC [A] | 0.020 | 0.024 | 0.021 | 0.018 |
| I @ Max T, 23ºC [A] | 0.133 | 0.309 | 0.265 | 0.175 |
| I, No-load @ –70ºC [A] | 0.070 | 0.115 | 0.085 | 0.046 |
| Mass [kg] | 1.11 combined | | 0.55 | 0.31 |
| *with attached Surveyor scoop with hardstops | | | | |

A unique feature of the IDA actuators that strongly enables low-mass designs are integral ball bearings fashioned from hard-anodized races machined directly into the actuator components. Inner and outer race cross-sections are each a "V"-shape. Each inner race is split down the center of the "V" in order to assemble the bearing and to allow for sandwiched shims. The shims accommodate tolerance build-up and allow for preloading via slight, deliberate deformation of the balls. This bearing system allows for the majority of actuator parts to be made of 7075-T7 aluminium rather than heavier materials such as steel or titanium that would normally be selected to match the CTE of standard bearings. Balls are made of Delrin® 500P and are installed as a full complement. Fig. 4 shows exposed Delrin® balls in the partially disassembled elbow actuator (some balls have been removed). Although this kind of bearing design is somewhat unusual and has limited load capability compared to standard bearings, it works well for the IDA and has heritage dating back to the Mars Pathfinder mission where similar integral bearings were used for the six drive wheels and four steering actuators on the Sojourner rover.

For the MPL robotic arm program [4], the basic integral bearing configuration was re-designed for each joint actuator to operate under cross-moment loading generated during arm operations. In addition to being used in the load-carrying output stages of the MPL/InSight actuators, a similar configuration of integral bearing is used to support the output stage of each actuator's planetary gearbox. A slightly loose ball fit (as opposed to a preloaded fit) is used for joints 1-3 so as to not over-constrain the harmonic wave generator bearing and the last stage of the planetary gears. For joint 4, an integral bearing fully supports the pinion gear driving the bevel gear. The bearing fit is approximately "line-to-line" in order to accurately center the pinion gear. The pinion gear races are cylindrical rather than V-shaped and there are two rows of balls to support pinion moment loads.

Gears and bearings within the planetary gearboxes are lubricated with Braycote® 604 grease, a special formulation of Braycote® grease with very good low-temperature performance. Braycote® 604 is no longer available, however, and this has been taken into consideration with regard to refurbishment (more on this later). Upon refurbishment, harmonic gears in joints 1-3 and the bevel gear in joint 4 will be lubricated with Braycote® 601EF Micronic grease. All Delrin® ball bearings throughout the four joint actuators are un-lubricated.

*Figure 4. Delrin® balls in integral bearing (some balls missing)*

Each joint actuator is equipped with a 50K Ohm conductive plastic potentiometer for absolute position feedback. Except for joint 4, all potentiometers shafts are mounted externally to the actuators. Potentiometer housings are connected to ground with flexural Oldham-type couplings riding in slots in the backside of the potentiometers.

Each joint actuator motor is equipped with a simple, non-quadrature encoder comprised of a photo-transistor and photo-diode. The motor shaft exits the back of the motor and spins a photo-diode "beam-breaker" which is pressed onto the motor shaft. The encoder assemblies are custom fabricated. Fig. 5 shows a partially disassembled encoder.

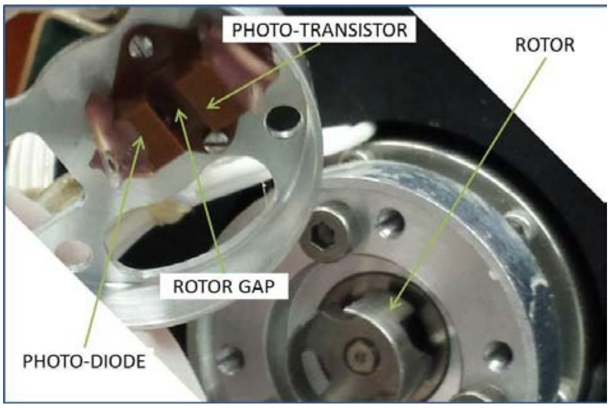


*Figure 5. Joint actuator encoder*

The encoders allow for fine-positioning of the IDA based on the high gear ratio of the actuators, but since they are simple and not configured to operate in quadrature, they cannot indicate motor direction. As a result, if an actuator reaches end-of-travel and the motor back-spins due to elastic windup of the gear train, the reversing encoder counts are additive with the forward-driven encoder counts. Fig. 6 shows the potentiometer and encoder on joint 3. The potentiometer in Fig. 6 requires additional attachment hardware installed at the next level of assembly to fix the non-rotating portion of the potentiometer.

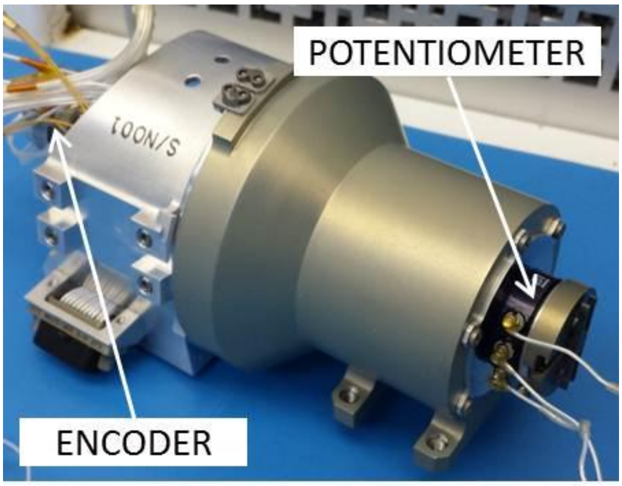


*Figure 6. Elbow actuator encoder and potentiometer*

### 2.2.2. Launch Locks

In keeping with the low-mass design of the IDA, the launch restraints are minimalistic. There is a completely passive 2-DOF elbow (joint 3) restraint and a spring-loaded 2-DOF wrist (joint 4) restraint which together fully restrain the IDA and its joint actuators at launch, with the exception of the output stage of joint 4. The degrees of freedom of the launch locks are arranged to allow for CTE differential growth along the length of the arm tubes. The restraints require no external power to trigger or operate; rather, a rotating cam surface incorporated into the end-effector attached to the output of joint 4 is driven to press against a mechanical trigger on the wrist restraint. Although the output stage of joint 4 is not locked at launch, it is prevented from rotating by the motor's magnetic detent holding-torque. Following release of the wrist restraint, joint 3 is driven to partially unlock joint 3 from the elbow restraint. Joint 1 is then driven to fully unlock the elbow area from the elbow launch restraint, allowing the IDA to deploy. Fig 7 shows the elbow and wrist restraints. Six threaded mounting holes can be seen on the output shaft of joint 4 where the scoop or other payload attaches.

*Figure 7. Elbow (left) and wrist (right) restraints*

### 2.2.3. Structure

Interconnecting structure between the IDA's joint actuators is fairly simple. The upper-arm and forearm tubes are made of XN-70 and XN-80 carbon-fiber composite material with wall thicknesses of 0.8 mm and 1.1mm, respectively. End-fittings are thin-walled titanium (the only titanium used in the IDA) and are bonded to the exterior of the composite tubes with Hysol EA 9309 adhesive. The original MPL arm used XN-70 for both tubes, but the forearm was redesigned for the Surveyor arm because of increased mid-span loading due to the addition of a 400-gram Mossbauer spectrometer mounted onto the forearm. Redesign included thickening of the forearm tube wall from 0.8 mm to 1.1 mm and the substitution of XN-80 for XN-70 due to availability at the time. Tubes and end-fittings were tested under load throughout the mission temperature range (–105ºC to +55ºC) during development of the MPL arm.

### 2.2.4. End-effector and Payload

The original MPL arm used a small scoop (approximately 500 grams soil capacity) which was attached directly to the output shaft of joint 4. The scoop incorporated a moving cam surface to trigger the wrist restraint as discussed. The scoop design remained similar for the Surveyor arm. Both arms also had a small Robotic Arm Camera (RAC) mounted on a pair of brackets at the end of the forearm in order to examine the contents within the main cavity of the scoop and within a small depression machined into the scoop digging blade. The current plan for the InSight IDA is to incorporate some form of scooping tool in case there is a need to interact with the rocks and soil to prepare the surface for instrument placement. The RAC will be removed and a new camera called the Instrument

Deployment Camera (IDC) will be installed close to joint 3 rather than near the end-effector. Additionally, there will be a grapple mechanism suspended from the end of the IDA to place the SEIS and HP3 instruments on the soil. The grapple mechanism will have its own deck-mounted launch restraint and will attach to the IDA with a soft coupling. Fig. 8 shows a conceptual picture of the IDA with the grapple placing the SEIS instrument on the Martian surface.

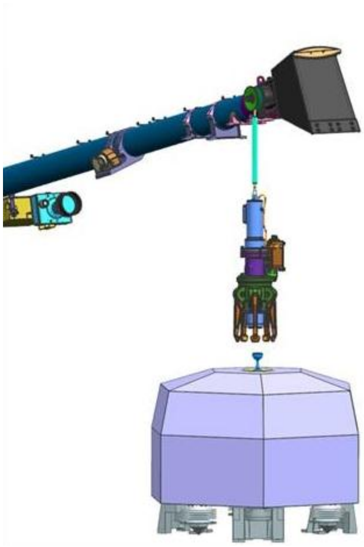

*Figure 8. InSight IDA grapple deploying SEIS*
*[image credit JPL/NASA]*

### 2.2.5. Flex-print

Flex-print construction is a Kapton® laminate, sandwiching rows of 0.1mm round wires permanently melded to micro-D style connectors. Current carrying capability for each 0.13mm wire trace is 1A. Shielding is created by electro-deposition of copper in very thin layers. There are five independent layers of flex-print starting at the IDA bulkhead. Three layers traverse the entire IDA and 2 layers terminate at joints 2 and 3. The flex-print is fabricated one layer at a time in a straight-line run. "Origami-style" folds are used to create right and left-hand turns of the flex-print as it winds throughout the IDA. This folding method was investigated for resistance to delamination before committing to such a method for the MPL MVACS robotic arm. Folding allows for a very simple collated construction (as opposed to printed circuit-board construction which MDA US Systems, LLC uses for its next generation of robotic arms), but scaling limits are reached when more layers are added. This is due to the thickness of the folds being disproportionate to that of the unfolded flex-print, which make installation and guidance difficult. Flex-print is guided and managed throughout the IDA via a lightweight cable management system integral to the IDA structure. Joints 1 and 3 use a clock-spring configuration of the flex-print to allow the flex-print to accommodate each joint's full range-of-motion. Joint 2 uses a simpler "S-bend" configuration because of the joint's more limited range-of-motion.

The cable management hardware also provides connections to the joint potentiometer housings via the couplings attached to the backside of the potentiometers.

## 3. IDA RECEIPT

The IDA was received by MDA US Systems, LLC from JPL at the end of January, 2013. The IDA had not been operated for approximately 13 years although the shipping container was opened several times over the years to take measurements and allow for visual inspection by JPL. Although, the IDA was flight-qualified years back, the unknowns associated with the long period of storage and dormancy were deemed unacceptable risks to the InSight mission. MDA US Systems, LLC was directed by JPL to partially disassemble the IDA for inspection and refurbishment following overall visual inspection of the IDA and a series of functional check-outs.

## 4. IDA VISUAL INSPECTION

Several days were spent closely looking over the IDA as delivered, secured in its launch restraints. Fig. 9 shows the IDA immediately after being received as shipped still in a locked configuration. The external condition of the IDA was verified as generally excellent. Special attention was paid to the condition of the flex-print, the launch restraints, the composite tubes (tap-tested for cracks), and the various runs of wiring and connector components.

## 5. IDA ELECTRICAL CHECKOUT

Before power was applied to the IDA for the first time, the flex-print was subjected to an electrical checkout verifying pin-to-pin conductivity and isolation, pin-to-shield conductivity and isolation, and resistance of wiring and actuator components (motors, potentiometers, PRTs, and heaters; encoders were not investigated at the time).

All measurements were shown to be in the nominal range except a few. One exception was motor resistance variance, which was to some degree expected due to position uncertainty of the motor brushes on the commutator bars, and potential surface oxidation of the brushes. Also, a shield-to-ground resistance path on the flex-print connected to the wrist actuator was higher than expected (partial delamination and/or cracking of the very thin vapor-deposited shield is theorized) but the situation was judged acceptable based on no impaired functionality or risk to the wrist actuator motor and encoder power and signal lines. The electrical checkout procedure finished by concluding that it was safe to apply power to the IDA and drive each of its joint actuators.

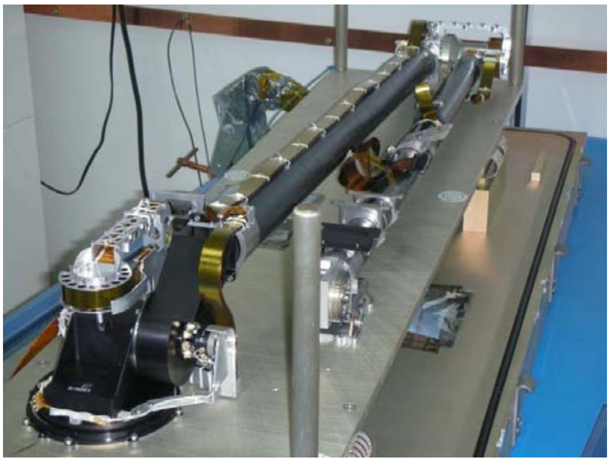

*Figure 9. InSight IDA upon receipt and unboxing*

## 6. IDA FUNCTIONAL TEST

Following completion of electrical checkout, the IDA was integrated with JPL-supplied electrical ground support equipment (EGSE). Each IDA joint actuator was driven though its full range-of-motion, with the exception of joint 2 due to interference caused by the shipping plate to which the IDA was attached. This was deemed acceptable because joint 2 moved through a majority of its range-of-motion. During joint motion, motor current was recorded using a simple data acquisition program on a laptop computer. In addition, potentiometer resistance for each joint was monitored to detect overt anomalous behavior (skipping dropouts, etc.) during joint motion.

Despite 13 years of storage, the IDA joint actuators ran without issue and each joint's current draw was within the expected range based on data from prior operations years ago. The potentiometers also worked properly without problems as far as could be detected by monitoring resistance using a multi-meter (more in-depth testing of the potentiometers will be discussed later). The dynamic, clock-spring portions of the flex-print expanded and contracted smoothly and the flex-print S-bend at joint 2 exhibited proper behavior. Fig. 10 shows the IDA in various orientations based on each joint's range-of-motion checkout. Joint 2 is shown at the limit of allowable motion due to the aforementioned shipping plate interference.

## 7. REFURBISHMENT

The directive from JPL was to disassemble the output stage of each actuator to assess the condition of the preloaded Delrin® balls, scheduled for replacement because of the 13-year period of storage, along with the tendency of the material to take a set under sustained contact pressure. Also subject to inspection were the dust seals, the harmonic gearing components, and the condition and quantity of the lubricant on the harmonic gear components and bevel gears.

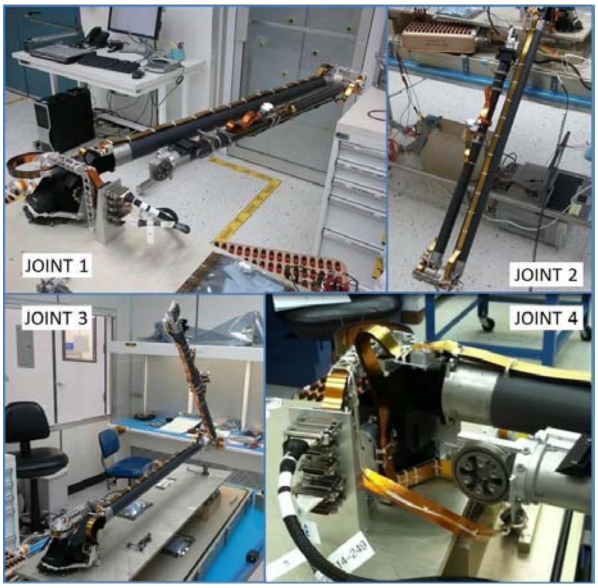


*Figure 10. InSight IDA functional checkout*

For all joint actuators, the motors and planetary gearing were left intact in order to preserve the Braycote® 604 grease which is no longer available and specially formulated for extremely low temperature performance (lower than -70ºC). The harmonic components were originally lubricated with Braycote® 602EF grease, which contains an $MoS_2$ additive for better wear properties, but due to some detected corrosion, which will be further discussed, the 602EF will be replaced with Braycote® 601EF Micronic grease.

Additionally, the launch restraint springs and any fasteners removed will be replaced. Any component suspected of needing replacement other than those mentioned will be considered of course, but certain components such as the planetary gearing and flex-print require a long period time to fabricate, and in the case of the flex-print, a large effort to re-install..

## 8. DISASSEMBLY

At the time of this paper, the flex-print has been removed from the IDA with most of the flex-print management hardware still attached; all of the IDA actuators have been disassembled down to the level discussed; the launch locks have been disassembled to remove internal springs; and the forearm and upper arm tubes have been set aside. Fig. 11 shows some of the disassembled components. It has been determined that the IDA is in generally excellent condition.

The Delrin® ball bearings, despite storage, appear to be round and uniform in size based on sample measurements from each actuator. The launch lock springs were load-tested and the spring stiffnesses were found to be within manufacturer's tolerance range although springs were kept under maximum preload.

There was no unintended migration of the lubricant within the actuators, despite a lack a barrier coatings.

There have been two prominent findings. The first is that certain areas on two of the three harmonic gears (from joints 2 and 3) have rust patches on the circular

*Figure 11. InSight IDA disassembled components*

splines. As mentioned, the harmonics are made of standard, non-stainless materials based on heritage practice. The rust appears to be present only on non-functioning surfaces of the circular splines, but an attempt will be made to slightly abrade the affected areas to try to remove some of the oxidized material. As mentioned, the older Braycote® 602EF will be stripped and replaced by Braycote® 601EF grease, which contains a rust inhibitor lacking in the 602EF formulation. The second issue is that there appears to be a lack of lubrication at the interface between the harmonic wave generator and the flex-spline. This is attributed more to the minimal lubrication originally applied to the harmonic components using a grease-plating process rather than lubricant degradation or evaporation. Other areas such as the bevel gear teeth in joint 4 were originally more thoroughly greased and still exhibit a well-lubricated condition.

Although electrical testing of the flex-print showed no anomalies, the flex-print will be subjected to a vacuum environment to expose delaminated areas if any exist.

## 9. REASSEMBLY

Reassembly in summary will involve cleaning and relubricating the harmonic components in joints 1-3, replacing the Delrin® balls in the output (load-carrying) stage of all joint actuators, replacing all removed fasteners, and re-dressing round-wire harnessing. Dust seals have been deemed in good shape and will be re-installed. There is an on-going investigation to replace the PRTs on each motor with a different version that mounts directly to the motor casing rather than on a G-10 (fiberglass) stand-off, which is the current condition. Thermal analysis shows the temperature lag due to the poor thermal conductivity G-10 material would be alleviated by bonding the PRTs directly to the motor casings as is now the practice. This effort will go forth if it is determined there is no risk to the motors in removing the bonded-on G-10 stand-offs or if it is feasible to leave the old PRTs as-is. Fig. 12 shows a motor with the attached PRT as it currently exists. Dual motor heaters can also be seen encircling the motor

*Figure 12. Motor PRT on G-10 stand-off*

## 10. ACTUATOR TESTING

All joint actuators will be subjected to dynamometer testing at the extremes of the operating temperature range of –65ºC to +45ºC and three points in between (–50ºC, –30ºC, and 0ºC). The actuators will be run at no-load torque at 10V, 20V, and 30V to characterize no-load speed arising from drag torque and at one-third, one-half, and maximum torque at 28V (see Table 1 for maximum actuator torques). At all temperature points, PRT and heater resistance will be measured. The thermal chamber will maintain atmospheric pressure and will be purged with $CO_2$ which is compatible with the motor brush material as formulated for the Martian atmosphere.

Other tests may be performed and are currently under consideration. These are static holding-torque, stop-and-hold torque, and thermal characterization of the joint actuators. Static-holding torque will measure the torque externally applied to each joint actuator at which the motor rotor begins to rotate. Stop-and-hold torque will determine the maximum external torque on each actuator at which the moving actuator will come to a stop when power is turned off, the motor leads are shorted, and the motor's magnetic detents stabilize.

The dynamometer test setup incorporates a breakaway clutch to protect the actuators in the event of an inadvertent over-torque or lockup of the torque-path of dynamometer. The test setup also uses a limit-switch module to trigger a shut-off event prior to an actuator being driven into its hardstops (there are no hardstops on joint 4). A reverse gearbox is used to amplify the drag torque from a magnetic hysteresis brake. Brake torque is controlled by a feedback loop closed around the torque transducer. The entire torque train drives an encoder used to gather actuator velocity data (actual encoder speed is reduced by the dynamometer gearbox ratio to determine IDA joint actuator velocity). Fig. 13 shows a schematic of the dynamometer setup for testing joint 1. Each joint actuator has a unique setup with its own range-of-motion limit-triggers and breakaway clutch set-point.

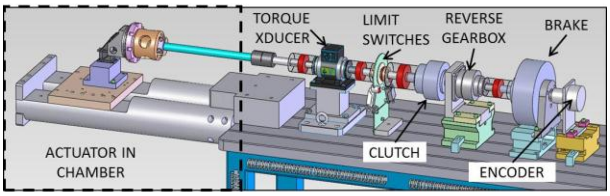


*Figure 13. Dynamometer setup*

## 11. POTENTIOMETER & ENCODER TESTING

Joint potentiometers will be tested separately at room temperature and ambient pressure. Potentiometer signal will be compared to an attached reference encoder across the approximately 350-degree useable range-of-motion of each potentiometer. Gathered data will be analysed for smoothness and linearity. Spares have been procured in the event of unacceptable performance by the existing potentiometers.

Encoders will be tested for signal strength and consistent signal development. As discussed, the encoder design is simple and does not indicate motor direction; however, the encoders do allow for precise joint output resolution due to the high gear ratios of the joint actuators (see Table 1). There is currently some discussion regarding replacing the encoders with more sophisticated quadrature units. The risks of doing so are being assessed, however, because the current encoder rotors are press-fit onto the motor shafts and removal will require special tooling and incur risk to the motors.

## 12. IDA SYSTEM-LEVEL TESTING

Following reassembly, the IDA will again be functionally tested. The IDA will undergo vibration testing, after which it will self-release from its launch locks. The IDA will then demonstrate a series of mission-related operations in a thermal-vacuum test chamber, starting with another release from its launch locks. At some point in the system-level test flow, stiffness testing will be conducted in order to measure three-axis rotational (i.e., angular) stiffness of joints 1-3 (joint 4 plays only a small part in overall IDA stiffness). Testing will involve applying a known force in several directions to the IDA tip and elbow while measuring corresponding deflections in two orthogonal directions at the tip of the IDA using precision transducers. Resulting data will be used to refine the IDA control model.

## 13. CONCLUSION

It is a unique opportunity to refurbish and recertify a 13-year old electromechanical system for an important scientific mission to another planet. The level of refurbishment is the result of a planned balance between complete disassembly and a testing-only stance. All investigations so far have yielded only a few concerns that will be addressed upon reassembly, proving so far the long-term robustness of the hardware. Successful dynamometer and post-reassembly functional testing will provide stronger evidence that the IDA is ready to fulfill its mission.

## 14. ACKNOWLEDGEMENTS

Acknowledgments are interesting because of the long heritage associated with this work. The author would like to thank the current JPL InSight team members and technical advisors. The author would also like to thank the JPL team members who originally designed and developed the MPL robotic arm for the 1998 MVACS experiment. It was an extremely valuable professional experience to work with and learn from such a well-versed group of engineers. The author would especially like to thank Robert Bonitz, David Braun, Mark Hetzel, and Don Noon, who worked closely with the author to develop the MPL arm which led to the Mars Surveyor arm and ultimately the InSight IDA.

## 15. REFERENCES

1. Excerpt from NASA/JPL Press Kit (2013). InSight Mission, NASA/JPL Document 400-1513, Rev. 2, pp1–2

2. Bonitz, R., Slostad, J., Bon, B., Braun, D., Brill, R., Buck, C., Fleischner, R., Haldeman, A., Herman, J., Hetzel, M., Noon, D., Pixler, G., Schenker, P., Thieu, T., Tucker, C., Zimmerman, W., Paige, D., (2001). Mars Volatiles and Climate Surveyor Robotic Arm, *Journal of Geophysical Research: Planets* (1991–2012) Volume 106, Issue E8, pages 17623–17634

3. Noon, D., Braun, D., (1998). "Long life" DC Brush Motor for Use on the Mars Surveyor Program, *32nd Aerospace Mechanisms Symposium;* pp185-196

4. Noon, D., Braun, D., Reid, L., (1999). Robotic Arm and Rover Actuator Systems for Mars Exploration, *JPL Technical Report Server, JPL TRS 1992+*.