Development of the Mars Exploration Rover Instrument Deployment Device

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Abstract

The Instrument Deployment Device (IDD) is a five degree-of-freedom robotic arm designed to give the Mars Exploration Rover (MER) the ability to gain physical access to the rocks and soil in the Martian environment. The IDD will accurately position each of four separate instruments attached to its end effector against and near geological specimens selected for scientific investigation. This paper describes the challenges encountered during the development of the IDD as well as the evolution of the design and the specifics of the hardware. These challenges were associated with fulfilling scientific requirements, packaging the IDD within a very confined launch volume, surviving launch and a high impact landing, protecting the IDD during rover driving activities, and keeping its mass as minimal as possible.

Introduction

The MER Mission

The MER mission is part of NASA's Mars Exploration Program, a long-term effort of robotic exploration of the Red Planet. The program seeks to take advantage of each launch opportunity to visit Mars, which occurs approximately every 26 months as the planets orbit the Sun. Scheduled for two separate launches between May 30 and July 12, 2003, the two rovers will be delivered in landing craft to separate sites on Mars in January 2004. Primary among the mission's scientific goals is to search for and characterize a wide range of rocks and soils that hold clues to past water activity on Mars. The spacecraft will be targeted to sites that appear to have been affected by liquid water in the past.2

After the lander has safely come to rest on Mars—in a manner very similar to that of the 1997 Mars Pathfinder mission—the rover will egress from the lander and spend the rest of its 90-Martian-day (approximately 2,220 Earth hours) operational life exploring the surface without further interaction with the lander.

The Purpose of the IDD

The (approximately 1-meter long) IDD functions as a dexterous appendage for the rover, delivering a cluster of four interchangeable scientific instruments to areas and specimens of interest. The four scientific instruments are the Rock Abrasion Tool (RAT), which grinds away a consistently sized, circular area on a rock specimen; the Microscopic Imager (MI), which takes extreme close-up images of rocks and soil; the Mössbauer Spectrometer (MB), which is used for close-up investigations of the mineralogy of iron-bearing rocks and soils; and the Alpha Particle X-Ray Spectrometer (APXS), which performs close-up analyses to study the abundance of elements that make up rocks and soils. In addition, the MI and MB are equipped with contact sensors that are activated when each instrument is positioned within a known, repeatable distance of the specimen. The contact sensors will serve the purpose of establishing the position of the IDD’s end effector with respect to the external environment while protecting the IDD, the

1 Alliance Spacesystems, Inc., Pasadena, CA.
2 Description taken from Jet Propulsion Laboratory MER website http://mars.jpl.nasa.gov/mer/overview/
MI, and the MB from inadvertent or overly forceful collisions with the specimen or an unintended nearby object.

The IDD is part of the Instrument Positioning System (IPS), which includes rover-mounted, stereoscopic Hazard Avoidance Cameras (Hazcams), and software that calculates from rover-based imaging where the rover and IDD are in relation to candidate specimens. Once a specimen is chosen and the topology of a specific area for study is mapped out, the IDD delivers the instruments to the rock or soil targets. For some rocky specimens, the RAT is used first in order to expose a fresh area of rock for study. The MI then takes images or an image mosaic of the target. Following this, the MB is pressed against the target for eight to twelve hours in order to gather compositional information. The APXS is then placed either near or against the target for three to twelve hours to similarly study the target's composition. Certain targets, particularly loose soils, do not require abrasion using the RAT; in these cases the MI is the first instrument positioned near the specimen, followed by the MB and the APSX. Ultimately, it is at the investigators’ discretion as to which instrument and instrument sequence are used.

After deploying from its launch locks, the IDD is free to extend and position itself within its working envelope. In the extended position, however, it is vulnerable to loads (up to 6g’s) generated when the rover’s wheels slip off rocks or steep hills. Before the rover is commanded to drive, the IDD must thus return to a partially constrained position—similar in pose to the launch position—in which it re-cradles itself by engaging certain features at the end effector and elbow joint into a passive re-stowing system. After the rover drives to the intended location, the IDD re-deploys from the cradled position and delivers the four instruments to the chosen target.

**Unit Production and Delivery**

Over a period of approximately two years, the IDD was conceived and an engineering model unit (EM) and two flight units (F1 and F2) were built and tested, along with actuators for a spare, third flight unit. Although the IDD system design underwent many changes throughout the first half of the two-year development period, the IDD concept remained kinematically intact with five degrees of freedom based on scientific needs for positioning its instruments with respect to the target.

**IDD Design Considerations and Drivers**

The design of the IDD is subject to several primary requirements based on the 90-day (Martian) MER mission as a whole. The IDD must:

- Survive launch loads as well as landing loads of approximately 42g’s due to the Mars Pathfinder airbag-style landing.
- Survive rover driving/maneuvering loads of approximately 6g’s.
- Operate within a temperature range of –70ºC to +45ºC.
- Survive a non-operational temperature range of –120ºC to +110ºC.
- Be as low mass as possible and allow for storage in a very confined launch volume nested underneath the rover.

In addition, there are many requirements and desired characteristics imposed upon the design of the IDD based on scientific operations. Based on some of the more critical requirements, the IDD must:

- Be capable of operating within an adequately large (based on scientific needs) volumetric “workspace” located a prescribed distance away from the rover. Within the workspace the IDD must be able to position the axis of the active instrument at any angle, within a
prescribed angular range, relative to the target surface normal vector. The IDD must also be able to press the RAT instrument against the target with a minimum of 10N force in order for it to maintain positive drilling pressure.

- Have a positional accuracy that enables it to position the “tip” of its instruments to within a maximum allowable ±5 mm sphere of error. In addition, the IDD must be able to return to a previous position to within a maximum allowable ±4 mm sphere of error.

- Be able to drive to a commanded position, settle, and hold position under gravitational loads and, in many cases, instrument usage loads as well.

- Be able to position itself in a pose deemed safe for rover mobility despite a failure of one IDD actuator. Specifically, a safe pose is one in which no part of the IDD is left below a prescribed plane coincident with the lower plane of the box-like rover structure.

- Be able to position the IDD instruments in order for them to access certain calibration targets and magnetic targets attached to the rover.

- Be able to recalibrate and regain its position in the event of an encoder count error or system power loss.

**Development Process for the IDD**

The design of the IDD was a multi-step iterative process, eventually producing a design that—among other characteristics—satisfies kinematic requirements, is of sufficiently low mass, fits within the allotted packaging volume, is capable of surviving launch and landing loads, and fulfills scientific operational needs. Figures 1a and 1b show key stages in the development cycle of the IDD from initial concept through finished hardware. From the start of development, the IDD possessed 5 degrees of freedom (DOF’s) in order to manipulate and position its instruments as dictated by scientific needs.

![Figure 1a. Development Cycle of the IDD](image-url)
The preliminary concept from JPL employed one actuator with its axis of rotation aligned with the IDD’s upper arm, but limitations on the resulting IDD workspace caused reorientation of the axis of rotation perpendicular to the IDD’s upper arm. Subsequent to this change, the IDD’s kinematic design, with specific regard to actuator-axis orientation, remained unchanged. Configuration 1 was a simple, kinematically representative version of the IDD used for studying link lengths, joint offsets, and operational viability. Configuration 2 incorporated much more of the developing IDD hardware, including early concepts for cabling and cable management. Configuration 3 improved upon Configuration 2 by generating for the scientists the largest workspace, much of which was the result of designing the instrument-end of the IDD such that it could swing past the forearm. This design, however, was found to be too heavy based on a detailed mass analysis, and thus Configuration 4—similar to Configuration 2 but with more mature hardware—was finalized into Configuration 5.

Figure 2 shows a flow chart depicting the general, iterative process used to arrive at viable designs for the IDD. Central to this methodology is the IDD system model, created using FEMAP/NASTRAN® software, and the ASI-developed kinematic analysis tool known as Workspace Explorer. In addition, SolidWorks® CAD software—used to design the IDD—is called upon to study reachability, stowage geometry and deployment kinematics. The results from these tools are applied to the developing IDD design, which is then modified and reanalyzed to provide inputs for the next design cycle.
Figure 2. Iterative IDD Development Process

Figure 3 shows the IDD NASTRAN® model subjected to simulated launch loads and with constraints analogous to launch-lock restraints. Shown are the representations for the actuators, the upper arm and forearm tubes, and the interconnecting structural components. The actuators are modeled using structural representations of their housings tied to spring elements that approximate gearbox torsional stiffnesses and ball bearing cross-moment stiffnesses. Ball bearing duplex sets in each actuator are approximated as linear, radial spring pairs with the spring constant set to that of the ball bearing at the proper “instantaneous” load point along its true, non-linear force/deflection curve.

Figure 4 shows a comparison of three different configurations of the IDD mounted on the rover with a large sector-like volume representing reachability and a cylindrical volume representing the scientific requirement for workspace. The sector volume is generated using forward kinematic equations specific to the particular configuration of the IDD and is limited to an arbitrary swath width once it protrudes well beyond the cylindrical workspace volume. Comparison studies such as this were carried out to assess the kinematic capability of the IDD and convey the information to the scientists. In addition, scientific requirements dictate that the IDD must be able to position the axis of the instrument in use within an angular range of ±π/4 radian azimuthally and zero to π/2 radian in elevation with respect to the rover straight-travel direction. The Workspace Explorer software is used to further investigate the five-dimensional space within the reachable range of the IDD. The first three dimensions are associated with where (in xyz-coordinate space) the IDD is capable of placing the tip of one of its instruments. The remaining two dimensions are associated with the azimuth and elevation angle of the instrument axis. The scientific necessity
to work in five-dimensional space is why the IDD—even from earliest concepts—requires five
degrees of freedom. Figure 5 shows the interface to the Workspace Explorer software, which
presents an overall view of the IDD’s orientation, the relationship of the instrument tip to the
workspace, and a close-up, spherical map depicting the achievable azimuth and elevation
angular range of the instrument axis once the instrument tip is placed at a point in space.

Mode 1, 87.0 Hz
Mode 2, 114 Hz
Mode 3, 157 Hz

Figure 3. IDD System Model Using NASTRAN® Software

Figure 4. Reachable Workspace in Relation to IDD Configuration
Figure 6 shows how the SolidWorks software is used to study operating kinematics of the IDD, specifically for the case of deployment from the rover. All the various joint angles are parametric and can be changed with subsequent updates to the overall IDD geometry. Clearances and distances can be measured and monitored so that when violations of allotted volume envelopes occur, it is relatively easy to understand which piece-parts or subassemblies are involved. This is very important because during deployment and re-stowing operations many parts of the IDD come within less than 1.5 mm of each other or the rover. In addition, some of the measured distances deemed critical are used as static starting points during dynamic analysis, and are thus incorporated into the analytical IDD model as special structural nodes that represent the closest approach between adjacent parts. Launch and landing simulations indicate whether or not these critical distances between adjacent nodes are unacceptably reduced or result in part-to-part collisions.
The same techniques used for studying normal operations are used to assess the kinematic limitations resulting from the failure of one joint. These limitations are examined to determine compliance with the IDD requirement dictating that the IDD, with four out of five functioning joints, is capable of positioning itself so that rover mobility is not in any way encumbered.

Looking back on the method for developing the IDD—which can be considered an appropriate methodology suitable for any lightweight, high strength, multi-degree of freedom mechanism—it can be seen that the actuators are components that require much analytical study, not only because they serve as prime movers, but also because their individual stiffnesses greatly determine the behavior of the IDD during all load cases. When the IDD is deployed and extended during operations, actuator compliancy is the greatest contributor to sag and first-mode natural frequency. When the IDD is kinematically over-constrained in its launch locks, the load path through the IDD system—and thus its individual components—is to a large extent a function of actuator stiffness local to the launch lock attachment points. Similarly, the stiffness of the rover itself, local to each of the two separate IDD attachment points, is an influence on load paths.

**Detailed Description of the IDD**

The mass of the entire IDD system, excluding the two pyrotechnic devices and the four instruments is approximately 4.2 kg. When fully extended it is approximately 960mm long from the axis of rotation of its base-mounted joint to the tip of its instruments. The IDD is built almost entirely from Titanium 6Al-4V due to the material’s high-strength to weight ratio and its compatible coefficient of thermal expansion as compared with gear and ball bearing steels. Figure 7 shows the IDD with some of its major components highlighted. A brush motor-based actuator drives each of the five joints, referred to as the Azimuth, Elevation, Elbow, Wrist and Turret joints. Seven layers of flexible cable, guided by and partially contained within a cable management system, supply all actuators and instruments with power and carry signals back and forth along the IDD.

![Figure 7. IDD System Features](image-url)
The IDD permanently attaches to the rover via a rover interface plate that also attaches to the Azimuth actuator output shaft, thus inverting the actuator and allowing its motor and outer housing to rotate. The Elevation actuator attaches to the Azimuth actuator via an interface bracket, and its output shaft connects to the Elbow actuator with a 32 mm diameter Titanium strut with Titanium end-fittings. The Elbow actuator has a feature that attaches to a bracket mounted on the rover during launch and landing. This coupling is achieved using a pyrotechnic pin-puller that serves as the structural pin connecting the feature to a bracket—via clevis and tang geometry—mounted on the rover. After the IDD is first deployed after landing, the same Elbow-mounted feature re-engages—albeit in a different manner using different engaging features—albeit with the same rover-mounted bracket when the IDD re-stows itself in preparation for rover driving and maneuvering. The Elbow actuator’s output shaft connects to the output shaft of the Wrist actuator (thus inverting it) with a 25 mm diameter Titanium strut with Titanium end-fittings, and the Wrist actuator housing connects directly to the Turret actuator housing.

The four scientific instruments are mounted on a common bracket that attaches to the Turret actuator output shaft. The Turret instrument bracket has a structural cap that couples to a release mechanism mounted on the rover interface plate. The release mechanism completely restrains the turret during launch and landing. Subsequent to release and in preparation for rover driving and maneuvering, the Turret cap has a feature that re-engages with a curved guide-way that is attached to the rover interface bracket.

Actuators
Each actuator is unique in its design, but all have shared features. All use Maxon RE020 brush motors equipped with magneto-resistive quadrature encoders with 32 counts per channel used for relative position sensing. Each motor uses an external detent system with a selectable peak torque (via varying the air gap by machining away the pole material) attached to its output shaft, and a planetary gearbox with a range of gear ratios, based on the number of stages used (with 4.333:1 ratio per stage). The detents are sized so that the IDD is capable of holding position in free-space as well as during operations where an instrument such as the RAT is pressed against a specimen. The configurable motor/detent/encoder/gearbox package was supplied by JPL. Each actuator has a potentiometer to provide absolute position information in the event of an encoder data error or system power loss. The Elbow, Wrist and Turret actuators incorporate custom-configured, integral, internal potentiometers, and the Azimuth and Elevation actuators use externally mounted potentiometers driven through an anti-backlash gear connection. Each actuator has a thin-film heater bonded to its motor and output ball bearing housing. The heaters, ranging approximately 2-4 W in power, are designed to heat the actuators up from –120 ºC (the coldest Martian temperature) to at least –70 ºC (the coldest actuator testing temperature) within one hour. Figures 8a is a photograph of the Elbow actuator and Figure 8b is a cross-section that highlights some of its components.
Figure 8a. Elbow Actuator

INTEGRAL POTENTIOMETER

DB ANGULAR CONTACT BEARINGS

3-STAGE PLANETARY GEAR [81.4:1 RATIO]
(ONLY 3\textsuperscript{rd} STAGE CARRIER SHOWN)

RE020 MOTOR

SIZE 11 CUP-TYPE HARMONIC GEAR [100:1 RATIO]

HEATER

Figure 8b. Elbow Actuator Cross-Section
Table 1 is a top-level summary of the five IDD actuators. Some of the performance characteristics were obtained during dynamometer tests (testing details are presented later in this paper) and are the approximate average of the four sets (EM, F1, F2 and F3) of actuators tested.

<table>
<thead>
<tr>
<th>Gear Reduction Type</th>
<th>Azimuth</th>
<th>Elevation</th>
<th>Elbow</th>
<th>Wrist</th>
<th>Turret</th>
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<tr>
<td>Gear Ratio</td>
<td>8137:1</td>
<td>8137:1</td>
<td>8137:1</td>
<td>1528:1</td>
<td>1528:1</td>
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<tr>
<td>Total Range of Motion [rad]</td>
<td>2.75</td>
<td>1.25</td>
<td>5.10</td>
<td>5.85</td>
<td>5.95</td>
</tr>
<tr>
<td>Static Torque Capability [Nm]</td>
<td>65</td>
<td>65</td>
<td>40</td>
<td>17</td>
<td>28</td>
</tr>
<tr>
<td>Operational Output Torque Capability(^1) [Nm]</td>
<td>45</td>
<td>45</td>
<td>20</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>No-load Speed +23°C, 28V [rad/s]</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
<td>0.61</td>
<td>0.61</td>
</tr>
<tr>
<td>No-load Speed –70°C, 28V [rad/s]</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.58</td>
<td>0.58</td>
</tr>
<tr>
<td>No-load Current +23°C [A]</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>No-load Current –70°C [A]</td>
<td>0.16</td>
<td>0.16</td>
<td>0.12</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Torque/Current Slope +23°C [Nm/A]</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>Torque/Current Slope –70°C [Nm/A]</td>
<td>140</td>
<td>140</td>
<td>140</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>No-load Mechanical Accuracy(^2) [rad]</td>
<td>0.0015</td>
<td>0.0015</td>
<td>0.0020</td>
<td>0.012</td>
<td>0.012</td>
</tr>
<tr>
<td>Min. Stop and Hold Torque [Nm]</td>
<td>28</td>
<td>28</td>
<td>20(^3)</td>
<td>5.6</td>
<td>3</td>
</tr>
<tr>
<td>Motor Detent Torque Strength [mNm]</td>
<td>6(^4)</td>
<td>6(^4)</td>
<td>6(^4)</td>
<td>6(^4)</td>
<td>2</td>
</tr>
<tr>
<td>Mass [g]</td>
<td>590(^5)</td>
<td>480(^5)</td>
<td>405</td>
<td>380</td>
<td>350</td>
</tr>
</tbody>
</table>

\(^1\)Based on highest level tested
\(^2\)Includes harmonic gear output profile error and hysteresis
\(^3\)Limited to output torque capability of actuator
\(^4\)Limited to maximum allowable torque strength
\(^5\)Includes external potentiometer assembly (approximately 40g)

Primary Structure
The IDD system is principally five actuators joined by tubular structural elements and attached to a rover interface plate, which carries all launch and landing loads except those that are distributed to the elbow pin-puller bracket.
The tubular elements are comprised of simple, 0.75mm-thick Titanium tubes slipped into and riveted to Titanium end fittings. A two-part epoxy adhesive is used to initially bond the end fittings to the tubes via precision tooling that aligns each end fitting pair, but the epoxy's strength contributions are ignored in subsequent structural analysis. The original design for the tubes used lighter carbon-graphite composite as the material in conjunction with structural bonding only to the end fittings. Analysis could not show, however, that the composite to Titanium adhesive bond joint would survive the temperature extremes, thus prompting the shift to Titanium tubes. This change significantly reduces the risk of failure at the interface at the expense of a manageable mass increase.

The rover interface plate was designed to solve the problems of interfacing at multiple separate locations on the rover. Because the restraints necessary to secure the IDD during launch and landing cause redundant load paths, loads flowing through the IDD system are a function of the rover’s stiffness. In order to minimize this effect, the rover interface plate carries loads transmitted by the Azimuth actuator as well as the Turret launch lock system, both mounted to it. The rover interface plate mounts to the rover via a pseudo-kinematic connection (three pins in three matching slots) designed to greatly reduce loads that are transmitted through the rover’s mounting plane and into the IDD structure. Because the rover interface plate, in effect, modularizes the IDD’s primary connection to the rover, the complete analysis is segregated into studying just the plate and the attached IDD. Otherwise, analysis would require consideration of the entire rover/plate/IDD connection, with the concurrent design of the rover being an important factor in providing proper boundary stiffness inputs for the IDD system model. Analysis showed that if a modular interface plate methodology was not employed, there existed cases where insufficient rover stiffness would increase the IDD’s loads to levels that could not be accommodated by any design deemed viable in the context of the aforementioned mass and packaging constraints.

Because the IDD is designed to be as low mass as possible, most piece-parts are machined with an average wall and pocket-bottom thickness of approximately 0.75mm. In addition, because the design strives for high load capability in a small packaging volume, all structural connections using threaded fasteners are supplemented by shear pins. This practice also guarantees that accurately aligned, co-fastened piece-parts do not slip relative to each other and compromise calibration of the IDD.

Launch-locks
During launch and landing, the IDD is restrained at the Turret and Elbow areas in order to protect it from large loads, especially during landing where it experiences approximately 42g’s when the MER lander, with its airbags deployed, impacts the surface of Mars. Figure 9 shows the IDD in its launch locked configuration during vibration testing.

The Elbow restraint is a simple clevis and tang arrangement, held together by the pin of a pyrotechnic pin-puller. This particular geometry translationally constrains the elbow area in all directions perpendicular to the pin. Free translation along the axis of the pin is assumed during analysis, along with all rotational degrees of freedom. The axis of the pin is "aimed" back at the center of the bolt pattern that attaches the Azimuth actuator to the rover interface plate so that potential binding due to redundant constraints is minimized. Figure 10 shows a detail of the Elbow restraint system.

The Turret restraint system constrains the IDD Turret in all 6 DOF’s by engaging three, slightly spherical-ended pins, arranged radically and equally spaced around the Turret, into three close-fitting bushings on the Turret cap. Two of these pins are each held engaged into the bushings via a length of wire rope that passes through the mouth of a pyrotechnic cable-cutter and is connected to a short lever that depresses the pin. When the cable cutter severs the wire rope, a powerful spring (approximately 175 N) pushes each pin out of its bushing. The third pin is stationary and, following the retraction of the two spring-loaded pins, the IDD drives off of it using its Azimuth actuator. Figure 11 shows a detail of the Turret restraint system in both locked and
deployed configurations. The stowed configuration includes the Turret cap without the rest of the Turret shown for clarity. The deployed configuration indicates the direction which the Azimuth actuator drives the Turret away from the restraint system.

![Figure 9. IDD in Launch-locked Configuration (shown on vibration test plate)](image)

![Figure 10. Elbow Restraint with Elbow Hook Engaged for Stowing](image)
Figure 11. Turret Restraint Stowed and Deployed
Re-stow System
Analysis performed at JPL shows that when the rover traverses the Martian surface it may generate up to 6g’s during events such as when it unintentionally slips down a steep rock face. Due to its extremely lightweight design, the IDD, once deployed from its launch locks, cannot handle such loads without additional cradling. The re-stow system partially restrains the IDD so that the effects of potentially damaging loads are reduced to safe levels. During re-stow, the Turret cap has a “T-bar” shaped feature that engages into a curved guide-way attached to the rover interface plate (refer back to Figure 11). As a supplement to the Turret re-stow arrangement, the hook that attaches to the Elbow actuator has a slotted feature—separate from the hole into which the pin-puller pin inserts during launch and landing—that engages with the re-stow bar on the pin-puller bracket (refer back to Figure 10). The process of re-stowing the IDD does not require extremely precise positioning of its joints; rather, the re-stow features are designed so that the IDD can “bump” its way into them using actuator current sensing to detect and control the collisions. The Turret T-bar engages first followed by the Elbow hook, which is then preloaded against the re-stow bar by slightly overdriving the Elevation actuator.

Contact Sensors and MI Dust Cover
The MB and MI instruments are equipped with contact sensors that, when depressed during contact with a specimen, trigger a housed micro-switch. In the case of the MB instrument, a contact plate that envelops its front contacts the specimen, and in the case of the MI instrument, a stiff wire push rod contacts the specimen. The rod is sufficiently compliant with respect to side loading to prevent damage to it or the sensor. The MI has an external lens cover that is driven by a small DC brushless motor (JPL-supplied) commanded in a stepping mode. Figure 12 shows a detail of each contact sensor’s contacting element and the MI dust cover mechanism.

![Figure 12. MI and MB Instrument Contact Sensors](image-url)
Cabling and Cable Management System
All power and signal cables to the actuators, heaters, and instruments are contained within seven layers of flexible, Kapton®-jacketed ribbon cable containing 227 total conductors and manufactured using printed circuit board methods. Each layer is a continuous strip with a single MDM-type connector on either end with the exception of one layer, which has several round wires used for grounding purposes protruding near one end. When laid out flat, each layer is comprised of several right-angle bends that conform to the shape of the IDD structure and actuators when installed. The seven layers of cables reduce down to four at the instrument end of the IDD, as the four instruments are the final destination for the longest individual cables. For the joints that have greater than 1.5p radians range of motion—the Elbow, Wrist and Turret joints—the cables are arranged in a clock-spring configuration within a housed spool. For the Elevation and Azimuth joints, which have more limited ranges of motion, the cable is arranged, respectively, in a fixed and rolling loop configuration. The layers of cabling are designed to precisely fit onto the IDD via the method of first constructing an accurate stereo-lithography model of the IDD, complete with joints that rotate through the proper ranges of motion, and subsequently fitting and adjusting plastic-sheet cable patterns onto the model until proper performance and fit is achieved. Figure 13 shows the outstretched IDD with the flexible cabling winding throughout the system.

Figure 13. IDD Flexible Cabling Management System
(Protective cabling covers and instruments not shown)
IDD Testing

The IDD testing program can be organized into three primary categories:

- Subsystem level testing to characterize and evaluate actuators and contact sensors
- IDD system level testing to further characterize and evaluate actuators
- IDD system level testing to characterize and evaluate the IDD system

Not discussed in this paper are many minor, non-actuator, subsystem tests such as resistance and continuity measurements of the flexible cables, continuity measurements to the electrical ground plane, spring force validation for the turret launch lock, etc. In addition, subsystem level structural tests were conducted to validate the bonded connections of certain small parts to theTitanium tubes.

Subsystem Testing

The contact sensors were functionally tested to characterize the stroke of the contacting element versus the switch activation/deactivation point in conjunction with the force necessary to depress the contacting element through its range of travel. This testing was performed at ambient pressure at temperatures of −70ºC, +23ºC and +45ºC.

All actuators were subjected to ambient pressure dynamometer testing throughout the operational temperature range of −70ºC to +45ºC following 1-hour temperature soaks at non-operational temperature limits of −120ºC and +110ºC. The following tests were performed:

- No-load current at no-load speed
- No-load current versus speed profiling
- Torque versus speed profiling
- Worst-case startup
- Static back-driving threshold
- Stop and hold threshold
- No-load accuracy

Dynamometer Setup and Configuration

Figure 14 shows a schematic of the testing setup used to ascertain actuator performance. A thermal chamber with a controllable temperature range of −140ºC to +120ºC uses a dry Nitrogen purge system to maintain a moisture-free, ambient pressure environment. Up to two actuators at a time are mounted on load carrying, cantilevered bars protruding into the chamber. Each actuator’s output shaft adapter exits the side of the chamber through a close-clearance hole and connects to a torque transducer coupled to three magnetic hysteresis brakes arranged in series. A removable weight and pulley system attaches to the far side of the final hysteresis brake in order to conduct tests that require sustained torque, such as back-driving threshold evaluation. Each of the two actuator drivelines is separately configurable for different combinations of brakes, sizes of torque transducers, and various output sensors such as a high-precision encoders. Data are gathered by a combination of a LabVIEW® software managing a data acquisition system, and separate, custom actuator drive electronics with a graphical interface that controls up to six actuators at a time.

Dynamometer Testing Relevance

As seen, standard tests correlating current/speed with torque were performed, as well as certain tests that verified properties specific to IDD system requirements:

The worst-case startup test requires the actuator to start up with twice the worst-case, Mars operations torque load after a one-hour soak at −70ºC. This soak immediately follows a one-hour soak at −120ºC. This test simulates IDD operations in which one of the instruments is left pressed against or near a specimen overnight in order to gather information over a 3 to 12 hour
(Earth time) period. Following this period of instrument integration, and after heating its actuators to a minimum temperature of –70ºC if necessary, the IDD will select another instrument to return to the specimen and gather additional data.

Figure 14. Actuator Dynamometer Setup

The static back-driving threshold test involves incrementally increasing the amount of weight attached to a pulley until either the actuator encoder (part of the motor/detent/encoder package) shows movement, or the actuator reaches its safe capability torque limit. This test ultimately determines the load limit at which the IDD can sustain a static pose, maintaining its own position under the influence of gravity combined with the forces necessary to press either the RAT or APXS against a specimen.

The stop and hold threshold test is conducted similarly, except the actuator’s motor rotates at 250 rpm (the minimum controllable motor speed as driven by the flight avionics system) in the direction that allows the actuator’s output shaft to lower the weight to the ground. As the weight is lowered, the actuator is shut off and the motor’s leads are shorted via the actuator drive electronics. An oscilloscope, connected to the actuator’s encoder signal circuitry, indicates whether or not the motor ceases rotation within one detent cycle (equal to \( \pi/2 \) radians), the success criterion for this test. Weight is incrementally added until the actuator experiences either a runaway condition or its motor fails to stop within one detent cycle. The necessary torque strength of each detent was determined using a spreadsheet program that simulated the dynamic effects of the detents combined with those of motor back EMF. This test determines IDD system load limitations as in the static back-driving test, but the limits correspond to loads under which the IDD can position itself immediately following a move using one or more of its actuators. Limits determined from this test are by nature lower than those of the static back-driving test due to the effects of motor rotor dynamics.

The no-load accuracy test is performed by connecting the output shaft of the actuator to a high-precision, relative position encoder and recording the differential between it and the encoder coupled to the motor rotor. This test verifies that the actuators are capable of operating within accuracies required to allow the IDD system to position its end effector within a permissible ±5 millimeter sphere of error. Since this test is conducted with no external torsional loading, the gearbox accuracies measured are for the most part only related to gear tooth tolerances, and are only a component of the entire accuracy budget allotted for each actuator. Unloaded,
dynamometer-level accuracy testing is necessary, however, to verify that the actuators are operating correctly with proper input/output correlation prior to installing them into the IDD system. Additional output error due to hysteretic behavior of the harmonic gear under a reversing load contributes to the total output error in the case of Azimuth, Elevation and Elbow actuators, and planetary gearbox backlash error similarly contributes in the case of the Wrist and Turret actuators, although backlash is often notable during no-load accuracy testing. Output error under load is investigated during system testing of the IDD, which is discussed later.

In addition to verifying that the motors and actuators operate with proper margins with respect to torque output, current draw, position holding, overheating, etc., the various tests return data that are extremely important for use in calibrating the encoder of each actuator via initialization against its hard stops. The data consist primarily of the relationship between actuator current draw and corresponding torque output as a function of actuator temperature. The encoder calibration procedure, which is performed by the Flight Operations Team at JPL, relies on each actuator running into either of its hard stops at a known, fixed torque regardless of temperature. Because torque is fixed, the windup of each actuator upon impact with its hard stops is consistent and can therefore be treated as a constant error that is subtracted from the actuator’s encoder position. The actual value of this error is discovered during calibration testing at JPL, which is key to characterizing the behavior of the IDD system so that if the absolute position of one or more IDD actuators is lost due to a problem with telemetry, joint position can be reestablished. This is accomplished by driving one or more actuators to either of its hard stops, which are each at a precisely known angular location.

All of the twenty total actuators (four sets of five different types) built and tested were run at no-load torque as well as three other torque loading points at temperatures of –70°C, +23°C, and +45°C. As a supplement, the engineering model actuators—the first five actuators built and identical to the flight versions—were tested at additional temperature points of –60°C, –50°C, –40°C, and –20°C in order to further characterize the torque/current/temperature relationship. The flight versions were not subjected to this additional testing in order to keep motor revolutions and lubricant pressure cycles to a minimum.

**IDD System-Level Testing to Characterize Actuators**

Geometric characterization testing was performed in order to determine the precise angular position (within 2-4 milliradians) of each actuator’s hard stops with respect to the local coordinate system of each IDD joint. This information is used for hard stop initialization, as discussed, and for confirming that each joint encompasses the specified minimum range of motion. This testing involves temporarily attaching several optical targets to the IDD and using a Leica® laser tracking system to measure the locations of the targets as the IDD is driven, joint by joint, though its range of motion. Figure 15 shows the IDD equipped with optical target mounting hardware. Figure 16 shows graphical output from ASI-developed software written to process the laser tracker point cloud data and recreate the IDD geometry, including hard stop locations.

Repeatability testing was performed in order to measure IDD repeatability error at its end effector, which is required to be less than 4mm. This test involves driving the IDD away from and then back to a known starting position using all five actuators. The location of an optical target mounted on the IDD’s end effector before and after the movement sequence is compared and a three-dimensional error vector is generated. This test, while only a relative—as opposed to an absolute—accuracy test, takes into account harmonic gear hysteresis and planetary gear backlash effects that were not examined during no-load accuracy dynamometer testing. This is only true, however, if the IDD’s joints are selectively driven in angular regions where gravity does not consistently bias away hysteresis or backlash effects.
Actuator ball bearings and structural components were not subjected to cross-moment (perpendicular to the axis of rotation) loading during dynamometer testing; rather, the IDD system was statically loaded with weights while positioned in various cantilevered orientations in order to cross-load several actuators simultaneously. Figure 17 shows one particular setup for static testing with the IDD oriented sideways and with two sets of weights attached. Certain maximum cross-moment loads produced on bearings and structural components during this test were achieved once more during vibration testing. Although the actuators are stationary during static and vibration testing, they are subjected to 1g operational loading during various functional
system tests in the clean room environment and the large thermal-vacuum chamber. These tests are performed throughout the operational temperature range and each joint of the IDD is driven through its range of motion.

Figure 17. IDD Static Load Testing with Weights

Heater effectivity testing was conducted in order to determine whether or not each actuator’s pair of heaters is capable of raising the actuator’s average temperature from –120ºC to –70ºC within an hour. For this test, the thermal-vacuum chamber is set to a temperature of –120ºC and a Mars pressure of 8 Torr is simulated using a dry nitrogen atmosphere (the Martian atmosphere is predominantly carbon dioxide, but CO₂ is difficult to use at lower temperatures). After the IDD is subjected to a minimum one-hour soak at –120ºC, all its actuator heaters are turned on using a 28V supply and actuator temperatures are monitored via thermocouples. All the IDD actuators heated up to an average temperature of at least –70ºC within an hour, and some motors encased within protective shields, such as those on the Azimuth, Elbow and Wrist actuators, reached temperatures as high as –30ºC in that same time period. Figure 18 shows the IDD installed into the thermal-vacuum chamber.
IDD System-Level Testing to Characterize the IDD System

System level testing was performed primarily at ambient temperature and pressure, with the exception of thermal-vacuum testing which was performed throughout the operational temperature range of –70ºC to +45ºC following excursions to non-operational temperature limits of –120ºC and +110ºC. The following tests were performed:

- Random vibration and sine burst
- Mars traverse
- Settling time
- Thermal-vacuum
- Target verification and contact sensor function

Random Vibration and Sine Burst Testing

The EM, F1 and F2 IDD were subjected to 3-axis random vibration at proto-flight levels while restrained in its launch locks. This testing is conducted to validate the IDD system analytical model and determine the IDD’s first natural frequency, as well as verify survivability of the launch environment. Accelerometers are attached to the IDD at specific locations corresponding to those earmarked in the analytical model in order to correlate actual and simulated dynamic behavior. Figure 19 shows the IDD mounted on the shaker slip-plate in preparation for Y-axis vibration. Figure 20 shows X-axis test data for one particular accelerometer (channel 1X) associated with the lowest natural frequency of the IDD, approximately 60Hz.

The EM IDD was subjected to a 40Hz sine burst test at approximately 38g in all three directions in order to simulate the airbag-style landing on Mars. Ideally, this test should be performed using a centrifuge because landing load frequencies are low enough to be considered pseudo-static and thus do not cause dynamic excitation. The sine burst test was only performed on the EM IDD because data showed that some areas of the IDD were excited to possibly damaging levels. The EM did not, however, indicate any damage or deformation during operations subsequent to
this test as well as vibration testing. Figure 21 shows the response at the IDD’s Wrist area to the sine burst in which overly high excitation loads were generated.

Figure 19. IDD Mounted on Slip-plate for Y-axis Vibration Test

Figure 20. Full-level (0dB) X-axis Random Vibration Response for Channel 1X, Showing the Lowest Natural Frequency of the IDD is Approximately 60Hz
Figure 21. Response of the Wrist Area to X-axis Sine Burst Testing, Showing Over-test Due to Structural Amplification. Test Level is 38g Peak, with Response Acceleration of 50 to 60g, with Instantaneous Peak of 86g.

Mars Traverse Testing
For the traverse simulation test, which simulates worst-case loads generated during rover driving and maneuvering, the EM and F1 IDD—in conjunction with added ballast mass necessary for load generation—is mounted in its shipping container on a plate attaching it to the container’s internal wire rope isolators. The container is tipped up on one edge and dropped in two different directions, lengthwise and widthwise, to create transient impulses simulating surface traverse events. The IDD is oriented in its re-stowed configuration during these drops. As a success criterion, it was required that the IDD’s re-stow features remain engaged throughout this test—which was demonstrated using video recording—in addition to the IDD operating nominally post-test. Both the EM and F1 IDD were tested successfully. Figure 22 shows EM traverse test accelerometer data from the final drop in the Z-direction.

Figure 22. Mars Traverse Test Filtered Acceleration Measurements in the Z-direction
Originally the test plan called for only the EM unit to be traverse tested, but a small change to the re-stow hardware (unrelated to this test) enacted prior to building the F1 unit necessitated its testing. This change was necessary after un-stow testing revealed the possibility of interference developing between the elbow re-stow hook and the elbow pin-puller bracket (refer back to Figure 10) prior to completing the initial un-stow move.

Settling Time Test
The purpose of the settling time test is to characterize the settling time of the IDD and to measure its natural frequency when deployed. The test is performed with the IDD in a fully extended orientation and with all instrument mass simulators attached at the Turret. This configuration produces the lowest natural frequency for the IDD and thus the longest settling time following perturbation. The Turret is instrumented with a single accelerometer, and a 455g mass is suspended directly below the Turret’s center of rotation with a short section of Nylon® line. The line is cut, carefully so as not to disturb the IDD through inadvertent contact or extraneous motion, and the IDD structure exhibits a free decay. Figure 23 shows the test in progress and Figure 24 shows the decay envelope generated from accelerometer data. Spectral analysis of the decay is used to determine the natural frequency of the IDD’s vertical bending mode. Figure 25 shows the spectral analysis results indicating that the IDD’s natural frequency in the fully extended position is approximately 3.5Hz.

Figure 23. Settling Time Test
Figure 24. EM IDD Settling Time Test Decay Envelope

Figure 25. Spectral Analysis of EM IDD Accelerometer Data Showing a Natural Frequency of 3.479 Hz
Although not a requirement, it is desirable from a scientific point of view—specifically with respect to accurately positioning the MI instrument in free-space—that the IDD has a settling time of 15 seconds or less to reach a displacement of 30 microns. The settling time test data suggest that this is achieved if the initial peak displacement is no more than approximately 200 microns. For an IDD natural frequency of 3.5 Hz, this corresponds with a velocity of 4.4 mm/sec at the Turret. Since the fully extended IDD creates a moment arm of approximately 750 mm, the Azimuth or Elevation actuator rotation rate prior to abrupt motor shutdown (analogous to the perturbation event caused by cutting the line, although not in magnitude) should be limited to approximately 5.9 milliradians/sec, or 0.056 rpm. The corresponding motor rate is 450 rpm. In other words, if the motor speed is reduced to 450 rpm or less prior to shutdown, the IDD will settle to less than 30 microns displacement within 15 seconds. If the motors are stopped while spinning at a higher rate, a longer time may be required for the IDD Turret to settle down to 30 microns displacement.

Thermal-Vacuum Testing
IDD thermal-vacuum testing was briefly addressed with regard to testing the effectivity of the actuator heaters and a reference to Figure 18, which shows the IDD installed into the thermal-vacuum chamber. The heater test is one of the series of tests that the IDD was subjected to while in the chamber. Within the chamber are two cameras and several high intensity LED light banks. A window at the front of the chamber allows for visual inspection of the IDD as well. The basic temperature/pressure profile (ignoring thermal ramp and lag rates) and corresponding test procedure is shown in Table 2. Except for heater effectivity testing, all tests in which the IDD was driven were preceded by a 6-hour soak at the operating temperature. Table 2 presents the testing information in a way that combines all the various tests performed on the F1 and F2 units. The F1 test program did not re-stow the IDD while it was in the chamber, and the F2 test program did not include +45°C in the temperature profile temperature.

<table>
<thead>
<tr>
<th>Time [hrs]</th>
<th>Chamber Temperature/Pressure [deg C] Torr</th>
<th>Description of Tests Performed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>+23 760</td>
<td>No Tests</td>
</tr>
<tr>
<td>4</td>
<td>+110 10⁻⁵</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>-110 8</td>
<td>1. Launch-lock release</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Un-stow from launch locks</td>
</tr>
<tr>
<td>26</td>
<td>-70 8</td>
<td>Heater Turn-on</td>
</tr>
<tr>
<td>36</td>
<td>-110 8</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>-110 8</td>
<td>Limited joint motion</td>
</tr>
<tr>
<td>54</td>
<td>-70 8</td>
<td>1. Joint ranges of motion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Target verification</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Contact sensor verification</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Re-stow for rover driving and maneuvering</td>
</tr>
<tr>
<td>66</td>
<td>+45 8</td>
<td>1. Joint ranges of motion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Target verification</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Contact sensor verification</td>
</tr>
<tr>
<td>72</td>
<td>+23 760</td>
<td>Manual stow into launch locks – End of testing</td>
</tr>
</tbody>
</table>

Launch-lock release, normally initiated using pyrotechnic devices, is accomplished inside the chamber using pneumatically activated versions of the pin-puller and cable-cutter located at the Elbow and Turret areas, respectively.

The F1 unit suffered a partial failure during the first un-stow movement that normally drives the Turret off of the stationary pin following the release of the two retractable pins (refer back to Figure 11). Although the Azimuth actuator was driven to produce this movement, and feedback
on the drive electronics showed the proper angular excursion at the Azimuth motor’s encoder, the Turret remained “hung up” on the stationary pin, thus causing the overall IDD structure to elastically deform. This problem was detected when examination of the drive electronics data showed that the Turret actuator had been back-driven approximately 0.03 radian and was confirmed by visual observation through the chamber window. It was decided to drive the Azimuth joint to the launch-lock position, and in the process the Turret released from the stationary pin with a slight “jump” signaling the release of strain energy. Following F1 testing, the stationary pin was redesigned with its engagement area slightly smaller in diameter and axially shorter in order to promote an earlier disengagement from the Turret during un-stowing. The problem, which occurred for the first time on the F1 unit during thermal-vacuum testing (possibly due to cold temperature binding caused by the IDD’s slightly non-kinematic geometry when stowed for launch), did not recur during subsequent testing of the F1 and F2 units.

The joint ranges of motion are tested by driving each joint to its rotational extremes and recording the angular excursion as indicated by the drive electronics. Although this was essentially accomplished during actuator dynamometer testing, testing the entire IDD subjects the actuators to cross-moment loading and verifies that the flexible cabling is performing properly without binding or electrical discontinuities or shorting. During earlier clean room testing of the EM unit, a problem with the flexible cabling at the Elbow joint was discovered. The clock-spring portion of the cabling that circumferentially wraps around the Elbow actuator housing was found to be too tight when the Elbow was driven to one rotational extreme, although the Elbow joint was able to move throughout its full range of motion. Further investigation determined that the design of the cabling, all of which was developed using a stereo-lithography model of the IDD, did not, at this particular location on the IDD, perform properly despite functioning satisfactorily on the model. The cause of the problem was found to be small differences between the actual IDD and the model, at the exterior area of the Elbow joint. These differences were due to late design changes not updated in the model. The flexible cabling was subsequently redesigned, re-fabricated and reinstalled onto the F1 and F2 units. The EM unit was not retrofitted due to scheduling constraints.

Target Verification and Contact Sensor Function

Target verification testing involves commanding the IDD to place one of its instruments (instrument mockups) onto or near one of the fixed targets attached to the structure supporting the IDD. These targets are representative of actual instrument calibration and magnetic targets mounted on the rover, and the IDD instruments must repeatedly visit them during their various calibration sequences and to examine magnetically attracted airborne dust. This testing verifies that the IDD can orient itself in a manner necessary to visit the targets and that the intended joint-by-joint sequence of approach is correct. In addition, the values of the various joint angles when the IDD instruments are at each target are recorded and used as a starting point for further testing and fine-tuning after the IDD is delivered and is operated using flight software. Figure 26 shows the MB instrument positioned on one of the magnetic target simulators during ambient clean room tests conducted to set the stage for identical tests within the thermal-vacuum chamber.

System level contact sensor testing is similar to target testing in that the MI and MB instrument contact sensors are each first positioned near, and then driven into one of the magnetic target simulators, thereby triggering the sensor and causing the IDD to stop movement and hold its position. This test simply verifies that the sensors are working properly through the flexible cabling and that the IDD responds to their signals. As with target verification testing, contact sensor testing was conducted in full view in the clean room prior to repeating the tests in the thermal-vacuum chamber.
Post Delivery Operations at JPL

Although the IDD units were operated, tested and calibrated to some degree prior to delivery to JPL, the flight team at JPL spent much time and effort further characterizing each IDD unit.

Some of this effort falls into the category of “fine-tuning” in which pre-delivery data are used as starting points for final mathematical characterization of each IDD unit. For example, values for individual joint stiffness (in the torsional and cross-torsion directions) and overall IDD settling time were first determined prior to delivery; this information was then used post-delivery as first-round inputs for sag compensation algorithms necessary to correct for gravitational effects on the position of the IDD’s instruments. These algorithms are designed to be generalized for any orientation of the IDD and rover and will thus function properly in Martian conditions. Other fine-tuning tests performed at JPL included IDD collision avoidance (with itself and the rover), target and hard-stop verification, motor current as a function IDD orientation, and precise end effector position as a function of motor encoder feedback.

In addition to fine-tuning IDD characterization parameters, post-delivery testing was necessary to unite the IDD with its controlling and monitoring elements within the flight avionics system. All of the IDD’s operational routines and motions were rehearsed, and any necessary corrections to the commanding software were made. These routines included deployment from the launch locks, re-stow for rover travel, specimen and calibration target visitation, and vector-aligned instrument motion. All testing was carried out at ambient and Mars temperature and pressure conditions.

A Post-Delivery Problem
After the F1 and F2 units were delivered to JPL, a cabling problem occurred on the F1 unit in which the flexible cable that forms a rolling loop around the Azimuth joint began to improperly extend itself when the joint was at one of its rotational extremes. This problem went unnoticed throughout the majority of IDD testing until finally the outer layer of the cabling fatigued causing an intermittent electrical short. The fatigue was due to unintended bending around a cable clamp bar with a small radius. The reason for failure was diagnosed as follows: although the rolling loop deployed satisfactorily during testing prior to delivery to JPL, the F1 unit differed from the F2

Figure 26. MB Instrument on Simulated Magnetic Target
unit in that the bracket that guided the rolling loop had been redesigned and replaced prior to delivery. This change was required in order to gain clearance between the rolling loop and the APXS instrument, which, as discovered during testing, rubbed against each other when the IDD was in its stowed (and re-stowed) position. The redesigned bracket forced the rolling loop into a slightly different position, thereby gaining the necessary clearance between it and the APXS instrument. Because the flexible cabling upon first installation was formed around the original guide bracket, when the redesigned bracket was installed the cabling displayed some curvature discontinuities indicative of a somewhat permanent set created by the shape of the original bracket. After the redesigned bracket was installed, the rolling loop worked satisfactorily, despite the permanent set. Following testing of the IDD with the redesigned bracket, the IDD was subjected to a 50-hour, +110ºC planetary protection vacuum bake-out that strengthened the set of the flexible cables comprising the rolling loop area—and the baked-out shape of all the cables throughout the IDD. This created enough additional resistance at the rolling loop to force the flexible cabling to improperly extend itself and bend backwards around the clamp bar. From the first time this improper behavior occurred, the cabling continued to operate in this mode of “least resistance” until the electrical short exposed the problem. The flexible cabling on the F1 IDD was then replaced and the cable clamp over which the flexible cabling was bending was redesigned to provide additional support that precludes the rolling loop from improperly extending itself. The redesigned clamp was also installed onto the F2 unit as a cautionary measure.

Conclusions and Lessons Learned

As expected, low mass requirements and tight packaging considerations often lead to a difficult implementation of a particular design concept. Beyond the challenges of creating parts and assemblies that are strong, lightweight, accurate, etc., there will most likely be limitations placed on operations, testing, or general performance.

This is the case for the IDD, with its operational limitations most evident in its actuators. Each actuator’s motor is capable of damaging its gearbox without current and speed limiting, and, in addition, current limiting is temperature dependent so that factors of safety for torque are never allowed to become overly generous at higher temperatures where gearbox efficiency is correspondingly high. Finally, another layer of current limiting dependent on the orientation of the IDD is employed. That is, for a particular pose that the IDD assumes, an actuator’s current is limited based on calculations that determine the torque level at which an actuator generates loads harmful to other actuators or IDD structure, such as when the IDD end effector inadvertently catches on a rock and the wrist actuator is operated. The dependency on software and telemetry sensors that this type of complex current limiting requires becomes unavoidable unless the system level decision is made that all mechanisms are to be designed to withstand all or most worst-case parameters (highest currents and voltages, fastest speeds, etc.), even at the expense of higher mass.

The process of calibrating an actuator’s encoder via initialization at hard stops is also challenging because, as previously discussed, the torque with which the actuator drives into its hard stops, which is a function of motor current and actuator temperature, must be known and consistent so that actuator windup remains consistent. Otherwise, resulting calibration errors will hamper certain critical operations such as re-stowing for rover driving/maneuvering. The IDD is designed so that its actuators are small and light, and hence employ large gear ratios that convert a small supply current error into a large output torque error. The output torque error in turn causes significant windup error due to relatively low gearbox/output shaft torsional stiffness in combination with the low stiffness of the hard stop structures themselves. An improvement would be to employ non-contacting, encoder style (optical) calibration markers that the actuator would sweep past, initializing the drive electronics at a known angle measured precisely during laser tracker testing. Mechanical hard stops would be included outside the range of the markers in order to prevent over-rotation of the actuator.
For a mechanism with multiple degrees of freedom, the development of an integral flexible cabling system is difficult and requires an adequate amount of time to thoroughly evaluate the behavior of the cabling while in motion. The overall project schedule must allow the cabling design engineer an adequate amount of time—as much as six months in the case of the IDD—to develop the electrical design and the physical shape of each layer of cabling. This effort is not isolated, however, because the final design of the flexible cabling, especially with respect to its shape, is necessarily concurrent with the design of the complex mechanical system throughout which it winds. While there is much design interplay between the developing cabling and mechanical systems, finalization of the cabling design occurs during the latter stages of the mechanical design. This is because a very accurate mockup of the mechanical system must be constructed in order to assure consistent cabling behavior. Even the thickness and stiffness of the flexible cabling layers used on the mockup should be as close as possible—if not the same—to those of the actual article. Only after the mockup demonstrates proper cabling fit and behavior can each cabling layer be fabricated, complete with end-connectors and any other electrical details. Because the design of the IDD required very tight packaging, there was not much room for error with regard to cable layer length—the multi-layer clock-spring areas around the Elbow, Wrist and Turret joints are each constrained internally by the actuator housing and externally by the protective containment spool; thus the annulus created drives and bounds the length of each cabling layer. Ideally, each annulus (or cabling containment region of any shape) should be large enough to provide the cabling layers generous clearance margins—accounting for perhaps four to five times typical cabling manufacturing tolerances plus cabling installation and fit-up tolerances—when the joint is at its positive and negative rotational extreme.

The incident of the cabling taking on a permanent set and behaving abnormally after the cable management design was finalized demonstrates that even when mockup-predicted performance appears acceptable, close scrutiny must be made during actual operations in order to assess whether performance is truly robust or marginal. A more robust design would not have been affected by cabling set or any other permanency effects following the 110°C planetary protection bake-out. In addition, the effect on flexible cabling of the bake-out itself.

Life testing of one of the IDD units was part of the original test plan, but time constraints forced its omission. This was deemed acceptable because the mission duration is only 90 Martian days and the lifetime number of output revolutions for any actuator, including testing and ground operations, will be no more than 500 at the close of the mission. Much of the design philosophy behind the IDD and its actuators takes this into account: harmonic gears are often operated at torques approaching their momentary peak torque rating; ball bearing stresses during operations are fairly high (up to 1.79 MPa, or 260 ksi), thus subjecting the Bray lubricant to pressure cycle degradation. Further testing would be necessary to determine at what point the actuators suffer either breakdown or unacceptable performance loss based on continuous operation under worst-case loading. If the IDD were to be designed to greatly exceed the MER mission lifetime, it is likely that in certain areas its physical size would substantially increase due to changes such as larger ball bearing sets, which are needed to reduce stresses to levels consistent with a long operational lifetime.