MECHANICAL DESIGN OF THE MARS PATHFINDER MISSION

Howard Jay Eisen, Carl W. Buck, Greg R. Gillis-Smith, Jeffrey W. Umland

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109

ABSTRACT

The Mars Pathfinder Mission was a great engineering achievement for the National Aeronautics and Space Administration (NASA) and the Jet Propulsion Laboratory (JPL) which built the Pathfinder Spacecraft and the Sojourner™ Rover. The mechanical design of the mission hardware was critical to the success of the complex entry sequence and landed operations. A wide variety of mechanisms were employed with varying technologies and heritage. These mechanisms have played a key role in the mission which has greatly exceeded expectations.

MISSION OVERVIEW

The Mars Pathfinder Mission is the first of NASA's Discovery series of "faster, better, cheaper" missions designed to perform exciting science on a shoestring budget. The challenge for JPL was to return to the surface of Mars within 3 years and deliver a mobile Rover for less than $196 million. The Pathfinder spacecraft was launched December 4, 1996 on a McDonnell-Douglas Delta II expendable rocket from Cape Canaveral Air Station. On July 4, 1997, Pathfinder successfully landed in the Ares Vallis region of Mars, an ancient outflow channel resulting from a catastrophic flood. Hours after landing, the Imager for Mars Pathfinder, built by the University of Arizona, yielded images of the surface which help confirm the theories about the formation of the site. The next day, the Sojourner Microrover deployed onto the surface and began its goal of taking measurements of elemental composition of rocks and soil using the U of Chicago / Max Plank Institute Alpha-Proton-X-Ray Spectrometer.

ARCHITECTURE

Cruise Stage

The Pathfinder Cruise Stage consisted of those elements which are necessary for interplanetary cruise but are not needed on the surface of Mars. These elements included:

- Solar Panels for Cruise Power
- Low Gain Antenna
- Propulsion Thrusters for Attitude Control
- Propellant Tanks
- Star Tracker
- Separation Devices / Launch Vehicle Adapter
- Heat Rejection System Pump Assembly and Radiators

The Cruise Stage provided the necessary consumables and power source which allowed for communication and control during the seven months of cruise but contained no independent systems. The Low Gain Antenna (LGA), for example, was an extension of the LGA used on the surface. The Spacecraft separated from the Cruise Stage prior to contact with the atmosphere. The Cruise Stage is believed to have entered the atmosphere soon after the rest of the spacecraft and burned up.

Entry, Descent and Landing

The Pathfinder Spacecraft plunged into the Martian atmosphere on a ballistic trajectory. This approach differed from that of the Viking probes, which decelerated propulsively into orbit prior to dropping into the atmosphere. The Lander element of the entry vehicle was protected by the ablative heatshield and blanketed backshell. A parachute was deployed by a mortar to slow the descent rate of the Lander and the heatshield was jettisoned.

Proceedings 7th European Space Mechanisms & Tribology Symposium, ESTEC, Noordwijk, The Netherlands, 1-3 October 1997, ESA SP-410 (October 1997)

The Lander was then lowered via a bridle until it was 20 m below the backshell. An altimeter signalled the firing of rockets on the backshell, which brought the Lander's descent to a halt 20 m above the Martian surface. Airbags inflated around the Lander, enclosing it in a cocoon. The bridle was cut 2.3 seconds after rocket ignition and the airbag-enclosed Lander bounced onto the surface. The highest loading experienced by the Lander was during the initial impact, where it saw 18.7 g's. The Lander came to rest after bouncing in excess of 16 times along a path of about 1000 m..

Landed Station

The Lander consists of four structural petals. The Base petal supports all of Pathfinder's electronics which are enclosed in a GrEp and foam enclosure. Mounted to the top of this structure is the High Gain Antenna (HGA), the Imager For Mars Pathfinder (IMP) and LGA. The side petals fold up around the base petal forming a tetrahedron. Side petals are aluminum machinings with E-glass/aluminum honeycomb sandwich panels covered by solar cells. With the Lander at rest after the airbags had cushioned the landing, the Airbag Retraction Actuators (ARA) winched cords sewn into the airbags to retract the bags out of the way. Once the bags were partially retracted, the Lander was prepared to use the Lander Petal Actuators (LPA) to right the Lander if it had stopped with a side petal down. That was unnecessary, however, since the Lander came to rest base petal down. The Lander continued to power the ARA's for a pre-programmed length of time then opened the petals. This exposed the side petals and their solar panels to the sky. The Lander then remained at rest until the Sun rose over the horizon several hours later.

Dawn brought power to the Lander and thus the capability to transmit data to Earth. Millions of people around the world watched as Jennifer Harris, Flight Director announced to the world in a very excited tone that, "We have EH&A Data!" This caused the second eruption of joy in the Pathfinder Mission Support Area when everyone realized that the Lander was healthy and transmitting engineering health and status data. Shortly thereafter, the Imager for Mars Pathfinder (IMP) began returning panoramic images by using the IMP Pointing Actuators for azimuth/elevation control.

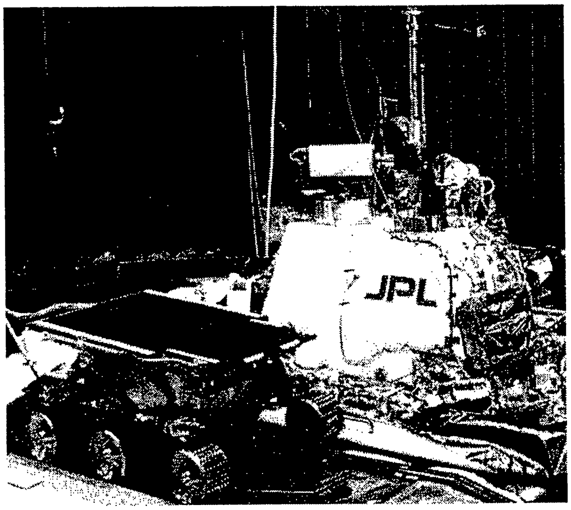

Figure 1: Mars Pathfinder Thermal Test: IMP stowed, Lander Petals, IMP and Ramp deployed

Rover

The Sojourner Mars Rover™, named after Sojourner Truth, a abolitionist and civil rights activist, is the first mobile robot ever sent to another planetary body. This six-wheeled vehicle utilizes the Rocker-Bogie mobility system which assures consistent weight distribution and torque transmission without the use of gears or springs.

The Rover stands 300 mm tall when deployed (Figure 1) but stows to 180 mm when mounted to the Lander's +Y petal (Figure 2). Sojourner, when unstowed, is 650 mm long and 480 mm wide with 130 mm diameter wheels, 80 mm wide. The Rover body is mounted to the Lander in a kinematic arrangement of 2 bipods (X/Z), one monopod (Z) and one shear pin (Y). The bipods and monopod are preloaded to the body via stainless steel cables tensioned to 1000 and 400 lbf., respectively. Once these cables were cut, the Rover was free from these restraints and could unstow. This operation involved driving the rear wheels forward while locking the others such that the body rose off the shear pin. This caused a rotation of one rocker-half relative to the other and in the process disengages a tab which allowed a spring activated antenna to deploy. At the top of travel, a spring latch tied the two pieces which comprised each "rocker-half" together, forming the now-rigid suspension. The Rover backed up slightly to disengage the wheel restraints and was ready to drive.

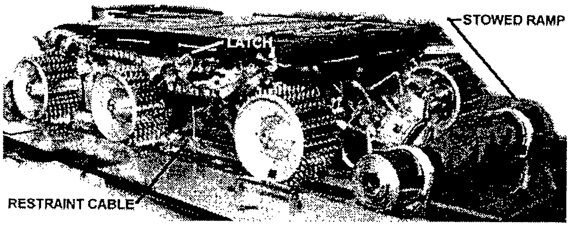

Figure 2: Rover Stowed for Launch

Egress to the surface occurred down the rear of the two ramps which rolled out like red carpets, giving the Rover safe passage over residual airbag, down to the surface which lies about 35 cm below petal level. The choice of which ramp to use was dictated by images taken from the IMP.

MECHANISM STUDIES

Rover Drive/Steering Actuator

The Rover required an actuator capable of driving the 11 kg vehicle distances of 100-1000 meters on the surface of Mars after supporting up to 100 meters of ground test. Furthermore, all hardware destined for the surface had to meet stringent biological contamination protection requirements to prevent the introduction of Earth-based life forms into the Martian environment. This limited the choice of materials and processing options. Rover electronics were sealed in the insulative Warm Electronics Box and conduction through copper wiring became a dominant heat leak. Therefore, a minimum wire interface for the actuator was desired. Lastly, the motor needed to be simple to control as the Rover computer was a modest performer, the 80C85.

After conducting a survey of available brush and brushless motors, the Maxon brush DC motor was selected for it quality construction, precious metal brushes and its unique capacitor commutation. In this system, a common capacitor is introduced between commutator segments. This allows the inductive energy stored in a reversing motor segment to be dissipated in a RLC circuit instead of as an arc. This is particularly important in a Martian 8 torr CO_2 environment where the Paschen voltage is at its lowest and arcing is rather easy. The capacitor thus has the ability to greatly reduce brush and commutator wear. The permanent magnet motor had the advantage of being a two wire device and not having temperature sensitive electronic components such as Hall Effect sensors. The Maxon motor was tested in extreme thermal environments for survivability (-125°C) and operation (-80°C) with changes in lubrication.

JPL used a LED/phototransistor pair with a rotating mask to create a one-bit relative encoder for motor odometry. This encoder mask, detent rotor and pinion gear were all mounted directly to the motor output shaft. The magnetic detent was necessary to provide holding torque with the motors unpowered like a parking brake. This was to maintain rover position, assuring that the Rover would not accidentally roll down a hill.

The gearbox was a 5-stage planetary sintered-metal system from Globe Motors. JPL engineers modified the stock Globe parts to remove weight from the ring gear/housing and by shortening the last stage pinion and sun gears. Miniature ball-bearings were also inserted between the planets and shafts of the first two high-speed stages to minimize friction losses. The gears were vacuum impregnated with Braycote 814 oil, chosen for its very low pour point. Since the total drive gear ratio was 2000:1, each encoder count corresponded to one motor revolution and only 0.2 mm (.008") of wheel motion.

Steering actuators (Figure 3) were identical to drive except the gearbox was followed by a 2:1 right angle bevel gear set to satisfy mounting and envelope constraints. The steering version contained the same detent assembly as the drive version but the one-bit encoder was omitted. Steering position was read directly via a conductive plastic Beckman potentiometer mounted to the output bevel gear.

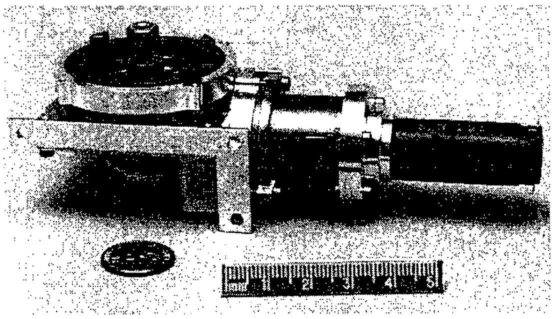

Figure 3: Rover Steering Actuator

Output bearings on both drive and steering actuators consisted of Delrin balls running in hard anodized aluminum races. This bearing arrangement was selected to minimize weight; approximately 10 g per actuator less than a conventional steel bearing. The races were machined into the output bearing, alleviating the need for some bearing retainers and thus reducing parts count. The Delrin balls were selected for their capacity to handle temporary overload (as in bouncing loads) without catastrophic failure. The bearings required no lubrication, and were tolerant to dust contamination and large temperature variations.

The assembled drive actuator weighed in under 180 g with a no-load speed of 1.5 RPM and stall torque of 70 in-lb. at 15.5V applied. Steering with stops installed at ±60° travelled lock to lock in 25 seconds and could supply 110 in-lb. of torque. Actuator testing included low temperature exposure to -90C and operation at -70C. During low temperature testing, as the motor resistance dropped, stall torque on these actuators increased to 90 and 160 in-lb., respectively. Life testing with eccentric loads surpassed 10 km of driving. Heaters were provided on the motors to decrease the current draw early in the morning but were never used during the mission.

<u>Lander Petal Actuator</u>

The Lander Petal Actuator (LPA) is a large, 5.7 kg (12.5 lb.), high-torque, mission-critical mechanism used to flip over and open the 350 kg Lander. The primary design criteria for this actuator was ultra high torque (12,000 in-lb.) in a small package with minimal mass. (Figure 4) Output speed was a secondary requirement to be less than two hours for both retraction and deployment. Electronic commutated, brushless DC motors were selected because of their high torque, high reliability, and availability of a design being developed for another project. The motor has a 0.14 Nm (20 in-oz) output stall torque driving a three-stage 49.3:1 spur gearhead. This motor/gearhead drives a 4:1 internal spur gearset inside the LPA (Figure 4). This outputs through a detent clutch to a 160:1 S-tooth Harmonic drive limited by a maximum (ratchet) torque of 1580 Nm (14,000 in-lb.)! Torque is transmitted to one hinge per petal via a titanium tube with square drive holes in each end. The output speed of this 31,552:1 overall gear ratio actuator is about 40 minutes per revolution. The operating temperature of the LPA is -40° to +35° C and was tested to -55° and +55° C with little change in speed/torque characteristics. This correlates with the findings from the ARA primary gearbox test which found that the Bray 602 viscous drag characteristics behave linearly down to -75° C. Kapton film heaters were incorporated into the flight design of the LPA to maintain the actuator above -40° C.

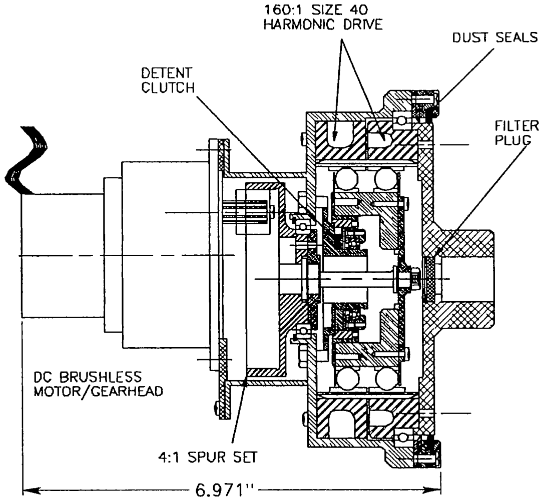

Figure 4: Lander Petal Actuator cross-section

The LPA detent clutch is driven continuously between the input to the wave generator and the housing when the actuator is powered. The purpose was to create enough backdrive torque to support the weight of the Lander when the actuator is turned off. It uses 4 opposing pairs of small compression springs pressing on rollers that ride on the internal surface of a toothed ring gear. The advantage of such a clutch is that its torque limiting performance is fairly independent of vacuum and temperature conditions and the running torque is slightly lower than the breakaway torque of about 1.36 Nm (12 in-lb.).

Several protective measures had to be implemented in order keep the abrasive Martian dirt out of the actuator. The dust seals use both an outer felt seal and an inner Vespel wiper. The actuator must vent upon launch and refill upon landing, so a porous metal plug was incorporated in the drive hub to allow air passage without dirt.

The new S-tooth Harmonic, which is able to transmit more torque than the standard toothform due to more tooth contact area, enabled the use of the lighter and smaller size 40. It was found through dynamometer testing that the flex spline would ratchet in the size 40 Harmonic gear before the motor would stall. This is undesirable, but was deemed acceptable because the torque output would be limited to the value necessary to lift the Lander. These actuators were dynamometer tested by attaching the actuator to a .61 m (24 in) diameter pulley, 4 m high on a static test tower and lifting stacks of steel weights. Cold operation was achieved by filling a purged Styrofoam box with liquid nitrogen and cold nitrogen gas and warmed again with a gas heater.

The circular splines exhibited acceptable performance after lightening from an as-delivered 1.02 kg (2.25 lb.) each to roughly .68 kg (1.5 lb.). The wave generator was hollowed out to make room for the detent clutch, which allowed the actuator to be much more compact.

Due to Harmonic gears being only 30-45% efficient from their characteristic sliding friction, they are sensitive to temperature effects on lubricant. The motor on the LPA only produces .141 Nm (20 in-oz) at stall. For another application on Mars Pathfinder, a similar motor with half the stall torque was used to drive a size 10 Harmonic drive directly. This actuator would not run below -50° C. The lubricant was changed to a very light grease plate of the Bray 604 low temperature grease, which corrected the cold operation problems. By comparison, the LPA 800 times the input torque to a larger size 40 Harmonic gear that was filled 10 to 20% with Bray 601 and there were no problems down to -100° C. The obvious lesson is that when using smaller, lightweight, low-torque motors the torque needs to be amplified before being transmitted to the less efficient Harmonic gear.

Bridle and Descent Rate Limiter (DRL)

The MPF Lander bridle sub-system performed three key functions during the entry, descent, and landing phase of the MPF mission, namely: 1) multi-body dynamic stability during rocket motor firing; 2) Lander deployment from backshell; and 3) Lander release from backshell/bridle. The Lander and backshell system were decelerated just prior to ground impact with three rocket assisted deceleration (RAD) motors mounted in the backshell. This two-body propulsive system did not use an automatic control system to maintain the net RAD motor thrust vector parallel to the Lander's path motion. Therefore, thrust imbalances between the three RAD motors would have a tendency to force the backshell to rotate about the Lander center of mass, which causes the RAD thrust vector to be pointed away from the Lander path of motion causing the desired delta-V imparted to the Lander to be degraded. In order to minimize this effect it is desirable for the Lander to be physically separated as much as possible from the backshell. It was determined based on tradeoffs on dynamic stability, deployment, and packaging volume that the bridle should be 20 meters in length.

In a simple sense the Lander deployment from the backshell is similar to rappelling off of a cliff. In both cases gravity is used as the motive force, and the descent rate is controlled by friction. Lander deployment from inside the backshell to its position at the end of the 20 meter Kevlar bridle during Mars descent was accomplished through the use of a descent rate limiter (DRL). The DRL is a passive energy dissipation device which was used to control the Lander's velocity relative to the backshell during Lander deployment. The DRL was a modification of a product manufactured by Frost Engineering, now part of Capewell Components, known as the descent device. Frost's descent device is a commercial product whose intended use is for personnel emergency egress from the crew compartment on aircraft such as the 747 freighter. This device is composed of a leading edge centrifugal brake, a descent tape housed on a spool, and a brake drum which also serves as a housing. The only modifications of the stock descent device for use on this mission were replacement of the centrifugal brake lead weights with tungsten weights, use of a 70 foot descent tape (rather than the stock 44 foot tape), and removal of the hand grips. Testing consisted of measuring the device's performance in a cold chamber with a low pressure carbon dioxide atmosphere. The final performance characteristics of the Lander deployment were such that the 350 kg Lander was deployed 20 meters from a 115 kg backshell in 10 seconds with a final Lander velocity relative to the backshell of less than 1 m/sec.

The third primary function of the bridle subsystem was separation of the Lander from the bridle This was accomplished by cutting the bridle with a pyrotechnically actuated cutter manufactured by Roberts Research Laboratory.

Separation Systems

The staging of the different elements of the Pathfinder system require precisely timed and coordinated separations. This involved the deployment of 53 separate pyrotechnically actuated devices. The pyro devices involved were Separation Nuts, Cable Cutters, Pyro-valves, Pin Pullers and Gas Generators. Each pressure operated device was powered by redundant NASA-Standard Initiators and various booster charges .

One such device was the 1/8" Cable-Cutter. Pyrotechnic Cable Cutters are piston devices that operate via pressure generated from a NASA Standard Initiator to drive a sharp steel blade through the target material against a soft metal anvil thereby severing the target material completely. This device was originally designed for cutting electrical cables across a separation interface plane. For the Rover to be deployed on the surface of Mars, the 1/8" Cable Cutters were used to sever tensioned stainless steel ropes which held the Rover against the +Y Lander Petal and were also used for cutting restraining cords which secured stowed airbags.

Another key separation device used on Pathfinder was the Separation Nut. Separation Nuts are piston/collet operated fasteners which use a segmented, threaded collet to hold interfacing bolts. Gas pressure from an explosive device, such as the NASA Standard Initiator, drives the segments apart and releases the interfacing bolt. Pathfinder used 21 such devices for jettisoning the cruise stage, releasing the heat shield, releasing the Lander and petal latches.

Imager for Mars Pathfinder (IMP) Deployment Mast

The IMP Mast assembly, built by AEC-Able Engineering, consists of a deployable triangular lattice structure, a base section, a tip plate and a launch restraint/release device. The Imager camera is mounted to the tip plate and the base section is mounted to the top of the electronics enclosure on the Lander base petal. Electrical cables to the camera are routed along the mast. The lattice structure consists of unidirectional fiberglass/epoxy rods, aluminum fittings and stainless steel diagonal cables. The mast is retracted before launch by twisting about the longitudinal axis. When stowed, it acts like a compressed spring. When released, the structure pushes outward to the extended position using its own stored energy.

The stowed mast, tip plate, and camera were restrained for launch and Mars landing by a pyrotechnically actuated pin puller. When the pin puller was actuated late on the second day of the mission, the mast was allowed to free-deploy as it lifted and supported the camera. As the mast was unrestrained during deployment, it took less than one second to go from a one inch stowed stack to a thirty inch deployed structure. This tremendous gain in height greatly improved the vantage point for the IMP images and cleared the camera of obstructions on the Lander itself.

IMP Pointing Actuator

The Mars Pathfinder Imager is mounted on an azimuth-elevation platform to allow full camera coverage of the landing area. The American Technology Consortium (ATC) provided identical actuators (Figure 5) for both axes. The actuators consist of 45° permanent magnet four phase stepper motors coupled through three stage planetary gearboxes. The motor design benefited from magnetic analysis and the utilization of neodymium-iron-boron magnets, both of which contributed to maximize torque margins within the given envelope. Torque margins were important in the design since the loss torque caused by the camera's harness was not clearly defined, particularly at the low temperature extremes. The actuator was designed to provide a minimum of 2.0 N-m of output torque, which was verified during testing.

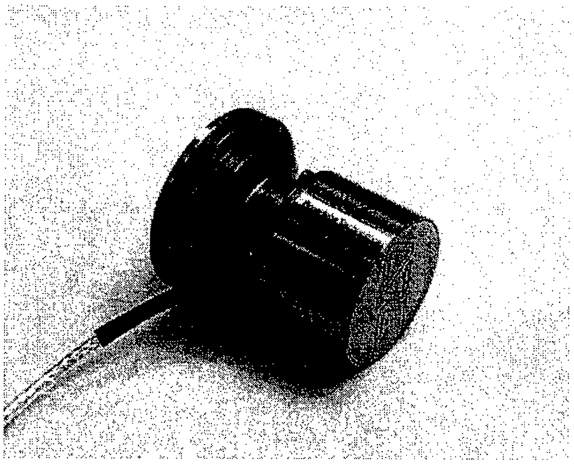

Figure 5: IMP Pointing Actuator

The planetary gearbox was a derivative of the gearboxes that ATC had provided for Pathfinder's airbag retraction actuators (ARA). The ARA's used ATC's precision gearbox coupled to the Rover's Maxon drive motors. The decision to partially rely on previously developed hardware was made to mitigate some schedule risk. Schedule risk was substantial since the delivery of flight hardware was required eight weeks after program start. Each of the planetary gearboxes' three planetary stages provides a ratio of 4.33:1 for a combined gear reduction of approximately 81.37:1. This resulted in an output step angle of 0.55°. The gearboxes are manufactured from high strength maraging steel for high torque capability and minimum weight. Several design features are provided within the gearboxes to optimize torque transfer and thus efficiency. Equal load sharing of the planet gears is promoted by free floating the planet carriers and by using no more than three planet gears per stage. Machining the planetary sun gears integral to the planetary carriers further enhances maximum torque capability of the gearboxes.

Rover Egress Ramp

The task of getting the Rover off the Lander required some substantial engineering effort. The Rover egress design needed to cope with petals which were not level and which could be more than a Rover's height off the ground. Airbag material was retracted following settling which drew the material under the petals causing them to be elevated when the petals were opened. Furthermore, the mass and reliability of these single use devices were critical to the mission success.

JPL selected Astro Aerospace Inc.'s experience in passively deployed masts to develop the Rover Egress Ramps. These Ramps used curved stainless steel channels used in Astro's Bi-STEM line of self-rigidizing structures. Two of these channels were separated by the inside dimension of the Rover's wheels, forming rails which constrained the Rover's motion. Outside these rails were laid flat sections of stainless steel sheet which served as tracks for the wheels to drive upon. These sections were held in place with battens and a shear carrying Kevlar mat. When the rail channels were opened by forcing the walls apart, the ramp could be rolled up into a 8 cm diameter roll (Figure 2). This roll was constrained to the Rover petal with cables. When the cables were cut, the energy stored in the rail sidewalls caused the entire ramp to unroll rapidly (Figure 6). Hook and loop fasteners placed along the tracks assured that the motion of the ramp was to unfurl and not expand in all directions. It did this by allowing peel but not shear between wraps on the roll.

Each 1 meter long ramp weighed less than 1.0 kg and was tested to assure safe Rover egress at angles of up to 30 degrees down to the surface and 30 degrees of twist.

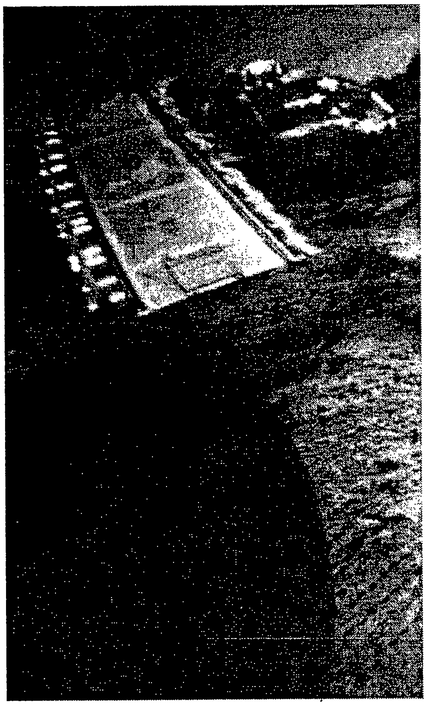

Figure 6: Rover Camera Image of Left Front Wheel with Deployed Rear Ramp in Background

Flight Performance

On the afternoon of July 4, 1997, the world watched as the Mars Pathfinder transmitter emitted a series of tones as different events during the entry sequence took place. The last set of tones indicated that the airbags had inflated and the Lander had come to rest on the base petal. Telemetry downlinked from the Lander over the next two days gave more details of the entry sequence and verified that indeed the bridle and pyro mechanisms had functioned properly.

Shortly after Martian sunrise, the IMP took the first panoramic view of the Rover still secured to the Lander and the surrounding terrain. Since the IMP field of view is approximately 14 degrees square, the IMP pointing actuators had to precisely move the camera head to allow for proper mosaicing of these small frames. The ARA's had partially retracted the airbags and the LPA's had opened the petals before sunrise, performing their functions flawlessly. When IMP images revealed that airbag material was blocking one Rover ramp, the LPA lifted the Rover petal, the ARA ran for a few more minutes and the LPA put the petal back down. The IMP mast deployed successfully and the IMP pointing actuators continue to provide azimuth/elevation actuation. Within the complete IMP system there has been a development of up to 30 arcseconds (= 30 pixels) of pointing error. The ground processing of IMP data now takes this into account and via a partially-manual process is able to correct for this effect when constructing mosaics. This pointing tolerance has caused the camera to occasionally miss objects such as the Martian moon Phobos when imaging with small subframes. Future uses of this system would most certainly employ some form of backlash control.

The Rover unstowed and exited the Lander petal via the rear ramp (Figure 7) on the second Martian day (sol). As of Sol 60, the Rover has driven more than 80 meters and the drive actuators have logged an average of 120 meters (including turn-in-place maneuvers). The drive actuators typically provide only 3-7 in-lb. but occasionally are called upon for 18-30 in-lb. These higher levels are equivalent to lifting the entire vehicle with just one wheel. A drive actuator reached a stall condition once when it is believed that a pebble wedged between the wheel and nearby structure. Reversing the wheel (automatically) eliminated the stall condition and the fouling material. The actuator appears undamaged.

The drive motor has served as a technology experiment as well. By turning the wheels one at a time in different soils, motor current has been used as an indication of force needed to shear the soil. These forces are compared to the applied load on each wheel calculated from the kinematic configuration of the suspension system. The result is the effective tractive coefficient of the soil which is to produce soil cohesion and angle of internal friction parameters. This direct measurement of soil properties has already yielded significant evidence of vertical layering of soil materials of differing strengths.

Throughout the mission, the mechanisms have met all their performance goals. In fact, except for the one drive motor stall, no loss of mission time or data has been caused by any of these mechanisms.

Figure 7: First IMP Image of Sojourner Rover on Martian Surface

Contributors

This authors would like to acknowledge the assistance in the preparation of this paper provided by:

- Jim Axtell, AEC-Able Engineering Company, Goleta, CA
- Don Noon, Jet Propulsion Laboratory, Pasadena, CA
- Doug Petercsak, American Technology Consortium, Camarillo, CA
- Joseph T. Sanok, Jet Propulsion Laboratory, Pasadena, CA