The Alpha-Proton-X-Ray Spectrometer Deployment Mechanism -- An Anthropomorphic Approach to Sensor Placement on Martian Rocks and Soil

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ABSTRACT

On July 4,1997, the Mars Pathfinder spacecraft lands on Mars and starts conducting technology and science experiments. One experiment, the Alpha-Proton-X-ray Spectrometer, uses a sensor head placed against rocks and soil to determine their composition. To guarantee proper placement, a deployment mechanism mounted on the Mars Rover aligns the sensor head to within 20° of the rock and soil surfaces.

In carrying out its task, the mechanism mimics the action of a human hand and arm. Consisting of a flexible wrist, a parallel link arm, a brush dc motor actuator, and a revolutionary non-pyrotechnic fail-safe release device, the mechanism correctly positions the sensor head on rocks as high as 0.29 m and on targets whose surfaces are tilted as much as 45° from the nominal orientation of the sensor head face. The mechanism weighs less than 0.5 kg, can withstand 100 g's, and requires less than 2.8 N·m of actuation torque.

The fail-safe coupler utilizes Cerrobend, a metal alloy that melts at 60° C, to fuse the actuator and the rest of the mechanism together. A film heater wrapped around the coupler melts the metal, and Negator springs drive the mechanism into its stowed position. The fail-safe actuates using 6.75 Watts for 5 minutes in the event of an actuator failure.

INTRODUCTION

The Mars Pathfinder mission, launched in December 1996, promises to reap a harvest of geological information about Mars. One of the nearly half dozen instruments making this science data possible is the Alpha Proton X-ray Spectrometer (APXS). Using a curium source and backscattering techniques, the APXS will determine the elemental composition of rocks and soil around the landing site.

To ensure information of high fidelity, the APXS sensor face must be aligned within 20° to the surface of each rock and soil sampling location, maintain a distance of 0.040 to 0.050 m from the sampling target, and be held in place for up to 10 hours. The most straightforward way to accomplish this task is to have a stowaway take the sensor in hand and place it on a rock or soil. The next best answer is the anthropomorphic APXS Deployment Mechanism (ADM).

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Consisting mainly of a flexible wrist capable of +/-25 degrees bending compliance in two axes, a parallel link arm, and a brush dc motor actuator with a gear ratio of 2000 to 1, the ADM operates in a 1.30 kPa CO_2 atmosphere at temperatures as low as -100° C. Using the Mars Rover as a transport (see Figure 1), the ADM both actively and passively positions the APXS sensor head on rocks as high as 0.29 m and on soil as low as 0.05 m below the bottom of the Rover rear wheels, while at the same time minimizing impact on Rover turn radius, ground clearance, and power. In the event of an actuator failure, a fail-safe mechanism composed of a Negator spring pack and a low-temperature-melting metal coupler decouples the mechanism from the actuator and retracts it into its stowed position. The entire mechanism fits in a 0.24 m long by 0.21 m wide by 0.14 m high envelope and weighs less than 0.5 kg.

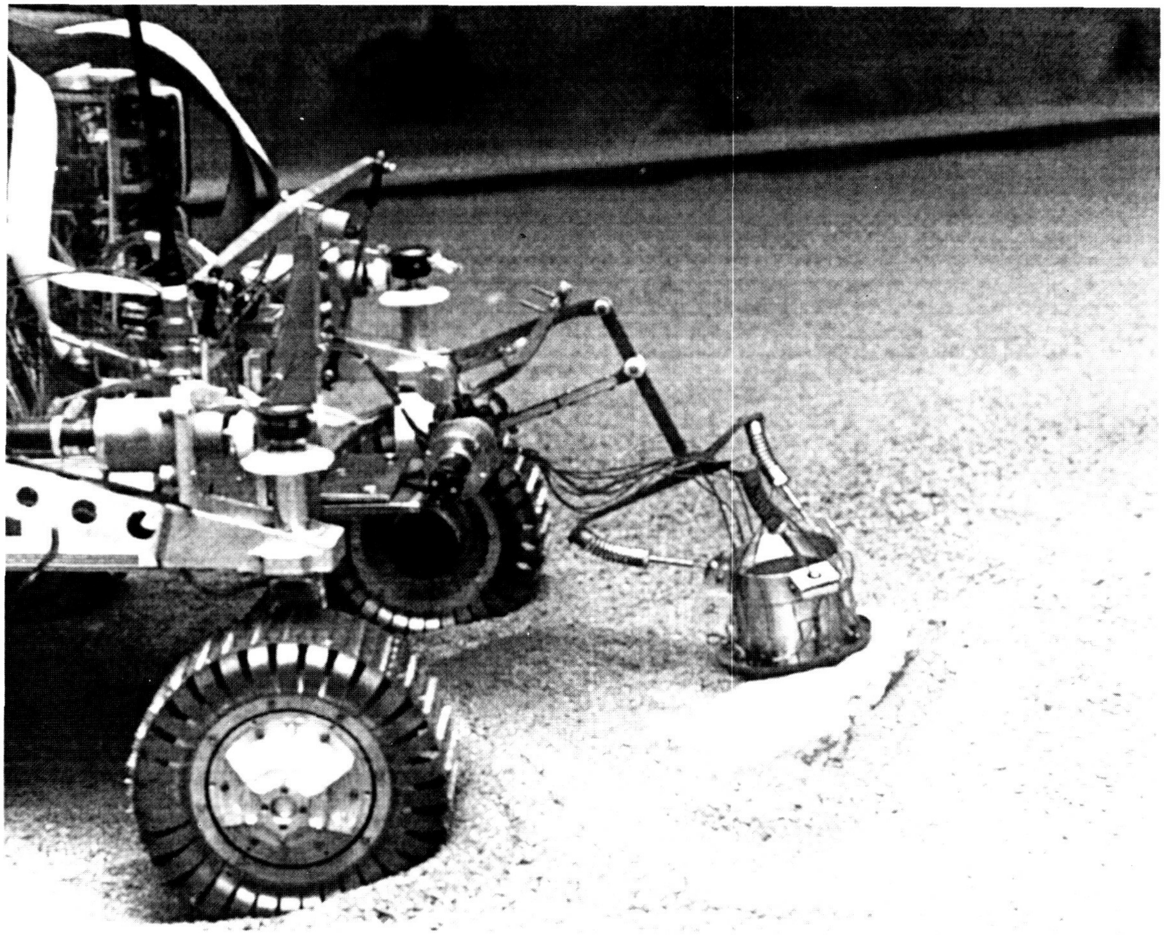

Figure 1. ADM mounted on the Mars Rover.

The ADM design underwent dozens of iterations to accommodate the performance goals of the instrument and to meet all the conflicting requirements levied by the APXS principle investigators, Rover developers, and Mars Pathfinder lander engineers. This paper explains the details of the final design, including the reasoning behind the choices made. At the end of the paper, test results show the performance of the ADM, providing empirical evidence of its capabilities.

DESIGN EVOLUTION

Flexible Wrist

Many technical challenges drove the ADM design evolution. The foremost obstacle was providing adequate sensor head compliance within the allowed volume. The problem is best illustrated by the following example. Imagine a person holding the sensor head with a 0.040 m long cylindrical spacer (see Figure 2) attached to the front. As the person contacts a rock with the front of the cylinder, the area of contact acts as a fulcrum. To align the sensor head completely with the surface of the rock, the person rotates the cylinder about the initial contact point until the cylinder is touching the rock in two other places. In completing the positioning, the person translates and rotates the sensor head, meaning that 5 degrees of compliance are required for the maneuver.

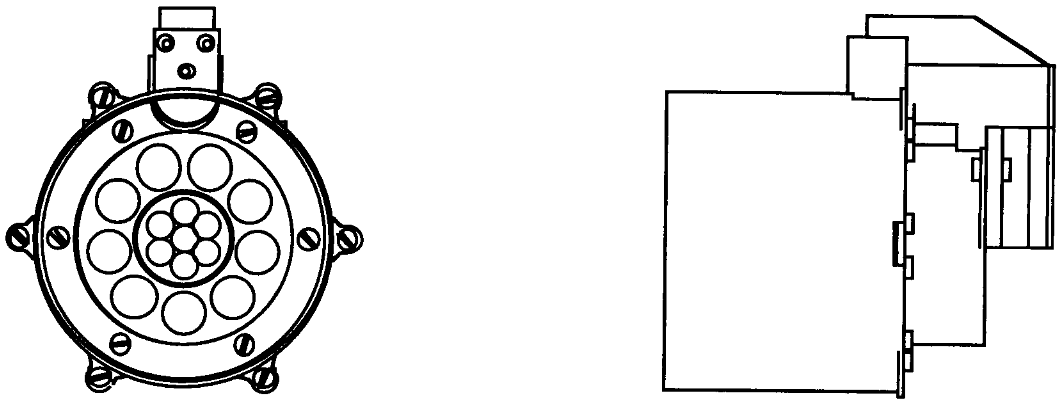

Figure 2. APXS sensor head with spacer attached.

This positioning operation is similar to the two-dimensional task that James Nevins and Daniel Whitney of Draper Laboratories studied[1]. They considered the robotic placement of a peg in a hole and what type of compliance is necessary in the peg gripper to compensate for robot positioning errors. As seen in Figures 3a and 3b, Nevins and Whitney noted that a gripper with parallel link supports is capable of compensating for translational errors, whereas a gripper with links angled inward is capable of allowing for rotational errors. The intersection of the lines down the longitudinal axes of the links is the initial center of rotation. Combining the two types of link supports as shown in Figure 3c, they produced a platform that accommodates both translational and rotational errors. If restoring force is required, they suggested that deformable wires be substituted for links, as depicted in Figure 3d.

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[1] Nevins, James L. & Whitney, Daniel E., "Computer-controlled Assembly", Scientific American, February, 1978, pgs 62-74.

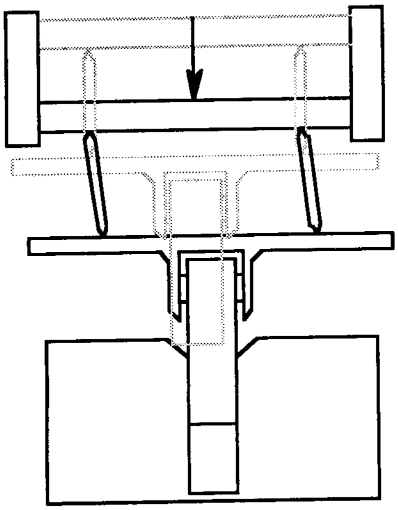


Figure 3a. Translational compliance.

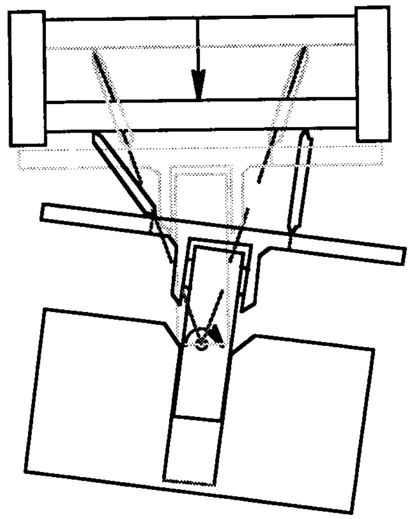


Figure 3b. Rotational compliance.

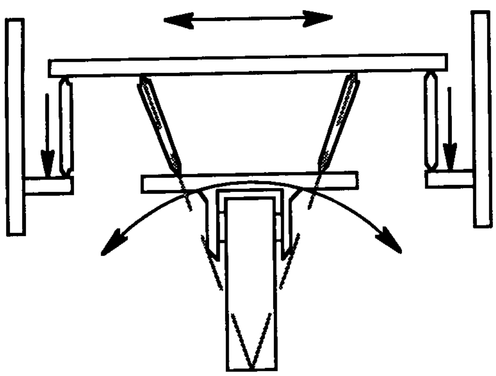


Figure 3c. Translational and Rotational compliance.

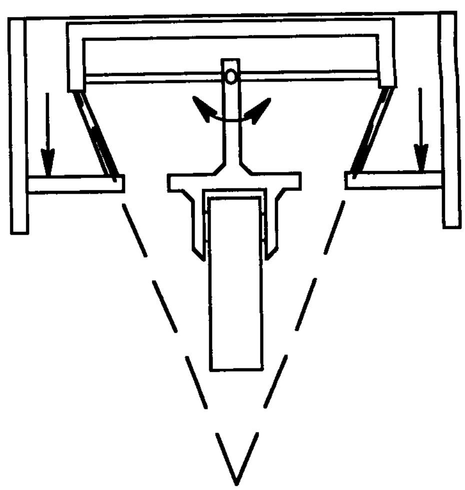


Figure 3d. Deformable wires used instead of links.

Applied to the APXS sensor head, Nevins and Whitney's link supports look like Figure 4a. Springs act as the restoring force in the figure. The size and weight of the support shown is prohibitive. But, by intelligent choice of the slanted link geometry, the translational compliance requirement can be reduced to below the amount of slop and flex in the mechanism, and the translational stage can be eliminated. Furthermore, by mounting the links on springs, the supporting geometry can shrink to the size and shape shown in Figure 4b.

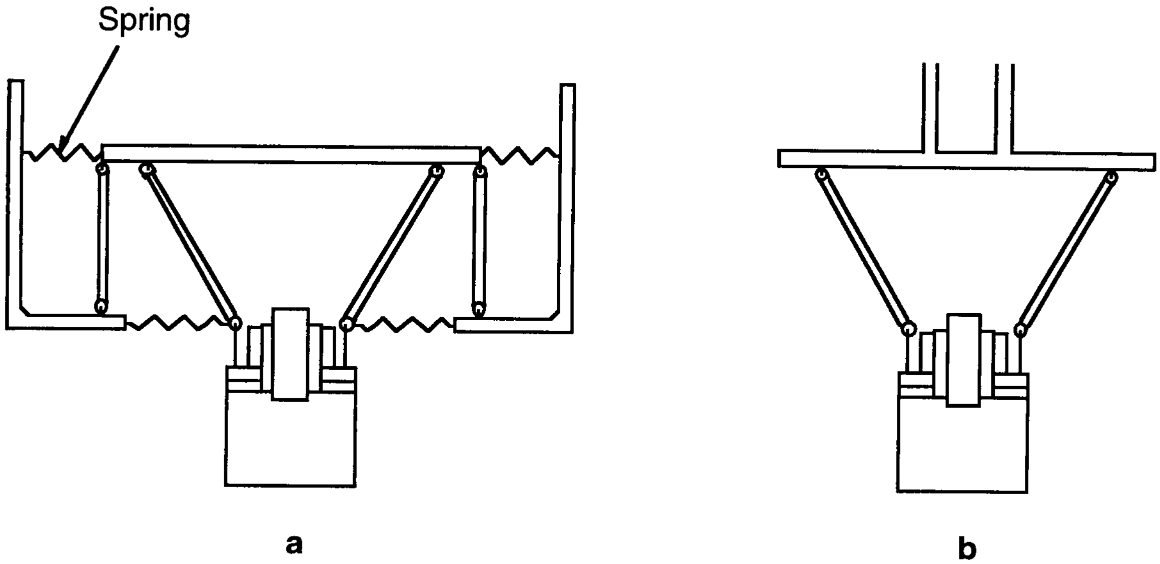


Figure 4. Nevins and Whitney's compound compliant support, APXS version. a) both translational and rotational compliant stages present; b) translational stage removed, links mounted on springs.

To determine the proper slanted link geometry, the kinematic equations of motion are solved until both the lateral translation target and the rotational capability target are met. Figure 5 illustrates the problem to be solved. For this design, translation less than 0.006 m and rotation of +/-25° are the targets. A geometry with A equal to 0.066 m, B equal to 0.125 m, and L equal to 0.053 m gives adequate results while still fitting into the design envelope.

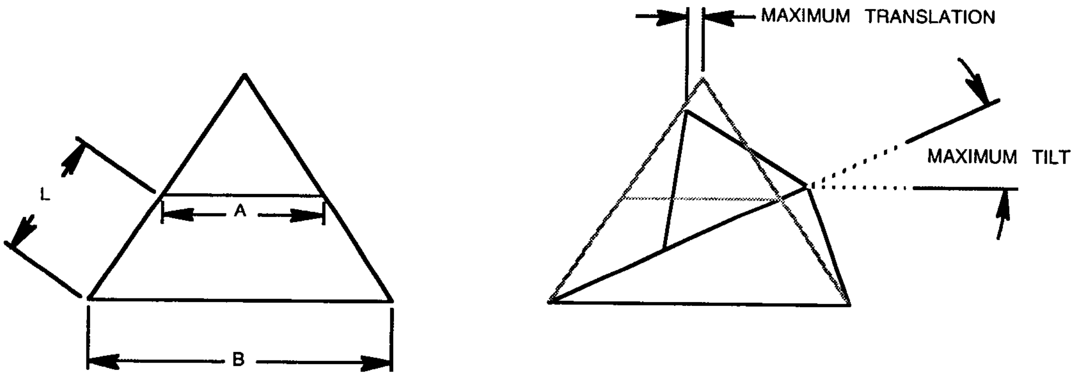


Figure 5. Wrist link geometry.

Converting the above kinematic study into three-dimensional hardware is straightforward, as links spaced 120° apart on a base support plate is the three-dimensional equivalent to the problem. Helical-cut springs mounted at the base of the links provide restoring force, as shown in Figure 6. Notice that the attachment points of the links to the sensor head are located so that the initial instantaneous center of rotation is in front of the sensor head, creating a stable compliance no matter where the sensor head contacts a rock.

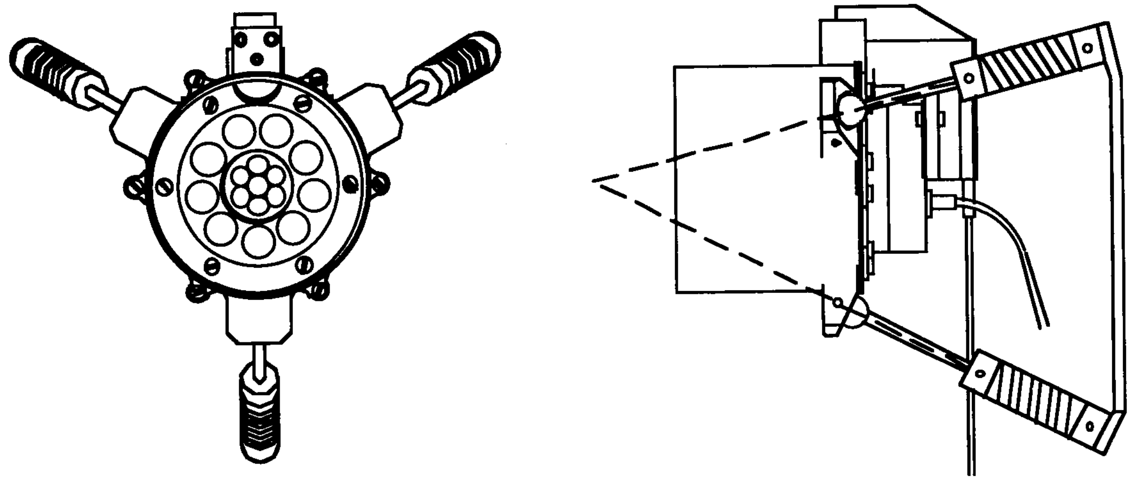


Figure 6. APXS flex wrist support. Intersection of dashed lines is the initial instantaneous center of rotation.

Alignment Indication System

Another design dilemma, whose solution goes hand in hand with the flexible wrist design, is alignment indication. A 0.04 m long cylindrical spacer mounted on the front of the sensor head easily insures that the low end of the 0.04 to 0.05 m sensor-to-target requirement is met. However, proper angular alignment requires a feedback system.

One design considered for this purpose consists of a 0.076 m diameter bumper mounted on three soft-spring-loaded plungers equally spaced around the cylinder (see Figure 7). As the bumper contacts its target, the plungers compress the springs and the bumper lines up flush to the target; then, the flexible wrist aligns the sensor head. When the plungers deflect, the body of each plunger immediately blocks the light path between an LED/phototransistor pair mounted at the base of the plunger. This sends a contact indication to the Rover control system. When all three LED/transistor pairs give a signal, then the sensor head positioning stops.

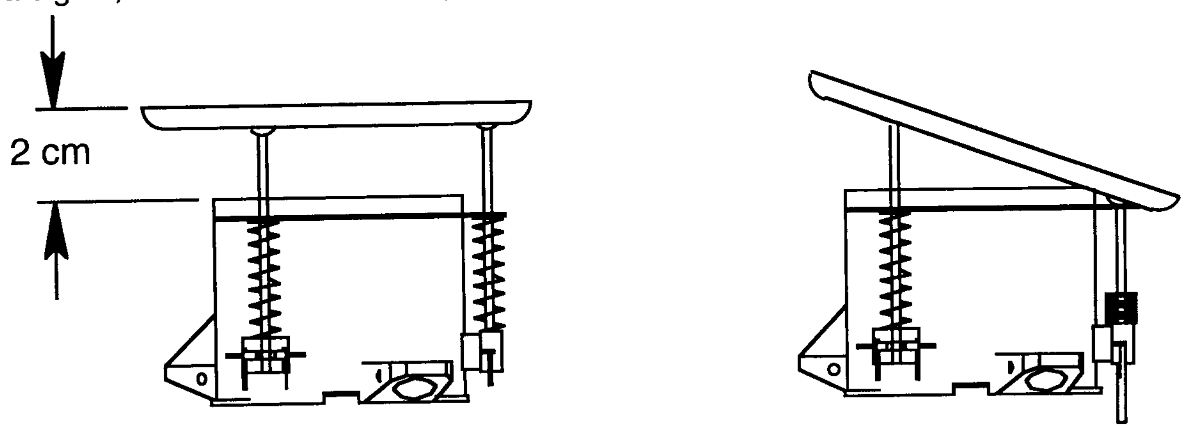


Figure 7. Bumper on soft springs. Alignment indication based on position.

To satisfy its requirements, this system must work successfully in the two extreme situations: an approach at an angle 45° off the normal to the surface, forty five degrees coming from the 25° of wrist compliance plus the 20° alignment requirement, and an approach straight-on. For the proposed system to work, the bumper must stick out 0.02 m past the front of the cylinder to allow for greater than 20° compliance. Also, the plungers must cause a contact indication after only a small amount of deflection, to take full advantage of the bumper compliance.

During the 45° off-angle approach, the bumper first complies to the target to within 25°. Then, the sensor head starts to rotate into alignment. At this point, one or two plungers are compressed as shown in Figure 7, but the third is not. As the sensor nears the 20° alignment requirement, the bumper becomes flush with the target surface, the third plunger starts to compress, the third LED/transistor pair gives a contact signal, and positioning stops.

For the straight-on approach, as the bumper contacts a rock, the three plungers deflect simultaneously, causing all three LED-transistor pairs to give a contact indication. Because the bumper is still protruding approximately 0.02 m past the cylinder at this point, the 0.04 to 0.05 m spacing requirement is violated. The cylinder must therefore move at least 0.01 m closer to the rock before the sensor head reaches proper alignment.

This design concept is faulty, for three reasons. First, the mechanism most likely is capable of aligning the sensor head more closely than 20°, as long as the original off-angle approach is less than 45°. Second, the protruding bumper increases the rover turn radius and increases the chance of the bumper snagging on a rock. Third, no feedback control exists for the last 0.01 m of travel during a straight-on approach.

A better design idea uses basically the same hardware, but has LED/transistor signal attainment based on force and not position; In other words, the LED/transistor pairs give alignment indication only after the flexible wrist support has positioned the sensor head the best it can and has either reached its end of travel or aligned the sensor head perfectly. Then, as the rover or actuator continues to push the sensor into its target, the force in the bumper builds up until stiff springs preloading the plungers compress. In this way, the plungers travel only 0.002 to 0.003 m, just enough for the plungers to block the contact switch light path, and the bumper protrudes a maximum of 0.005 m past the front of the cylinder. This scenario works as long as the sensor head approaches the target within 45°.

An important aspect of the alignment indication design is the shape of the bumper. One school of thought is that the bumper should be as smooth as possible to prevent it from catching on something. However, the bumper often needs to catch on a rock feature before the wrist can start aligning the sensor head; otherwise, the sensor head frequently ends up sliding over the rock surface. Another viewpoint is that the bumper should be pointy, like a set of pencil-shaped pokers. This works well on rocks, though the cross-sectional area necessary for the sensor head to align to the fine sand surface of Mars is nonexistent. Combining the two ideas results in a bumper shaped as shown in Figure 8. The sharp edge on the front surface is excellent for rock positioning, the frontal area of the bumper is sufficient for soil samples, and the smooth backside helps prevent the bumper from snagging during retraction.

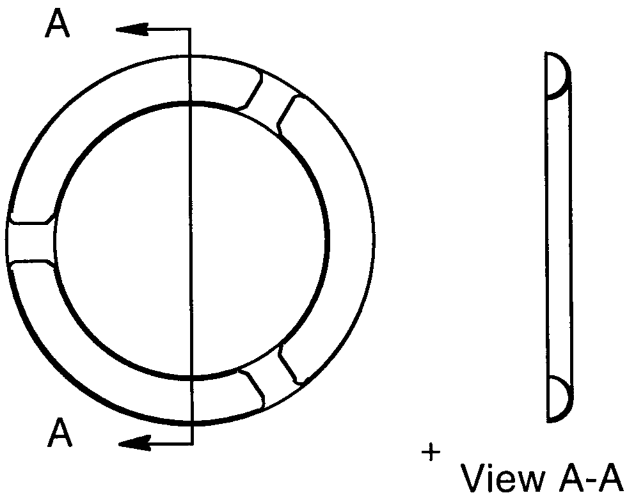


Figure 8. Bumper shape.

Vertical adjustment

In actively positioning the sensor head, the mechanism must be able to do four things: first, the mechanism must be capable of pulling the sensor head in close to the rover to minimize rover turn radius; second, the mechanism must be capable of extending the sensor head sufficiently past the edge of the rover solar panel so that the solar panel does not hit as the rover moves the sensor head into a rock; third, the mechanism must be capable of raising and lowering the sensor head to varying rock levels; and fourth, the mechanism must move vertically in its final motion down to the soil surface, not in a sweeping fashion, to eliminate the possibility of wedging the sensor head into the ground like a door stop, and to impede the bumper from scooping up dirt. Throughout its motion, the mechanism should keep the sensor from pointing upward, as the sensor is hypersensitive to direct sunlight and falling dust.

Ideally, the active positioning part of the ADM should move the sensor horizontally away from its stowed position, rotate it 90°, and then move it vertically down to the surface (see Figure 9). Mimicking this motion in a simple mechanism is tricky. Chain drives, clutches, pulleys, and parallel links can all do the job to one extent or another. The best answer however, due to its simplicity, is a parallel link system.

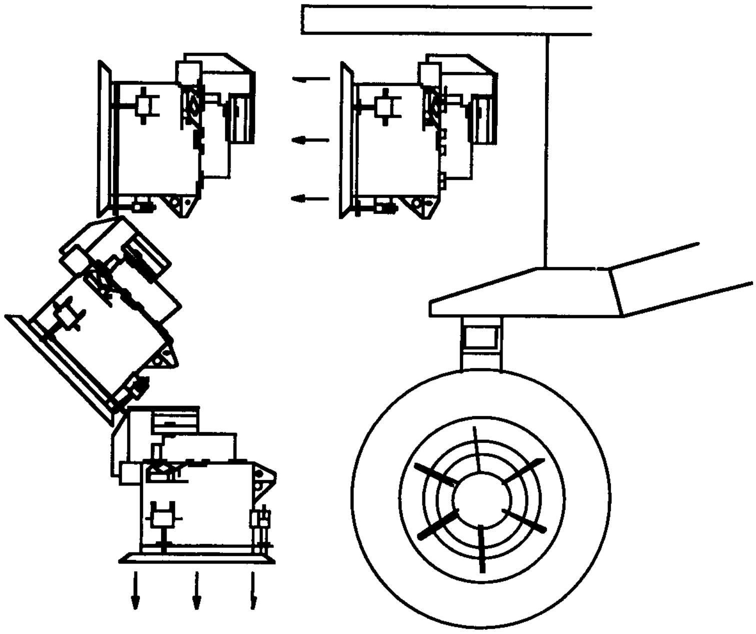


Figure 9. Ideal travel of the sensor head.

Parallel links of equal length most closely achieve horizontal or vertical motion at the apex of travel. Therefore, parallel links positioned as shown in Figures 10d and 10a accomplish the critical vertical motion of the sensor down to the surface and the less critical horizontal motion away from the rover. To create the sweeping transition between the two linear motions, one of the parallel links hits a stop, allowing the entire assembly to rotate about the drive axis, as shown by comparing Figures 10b and 10c.

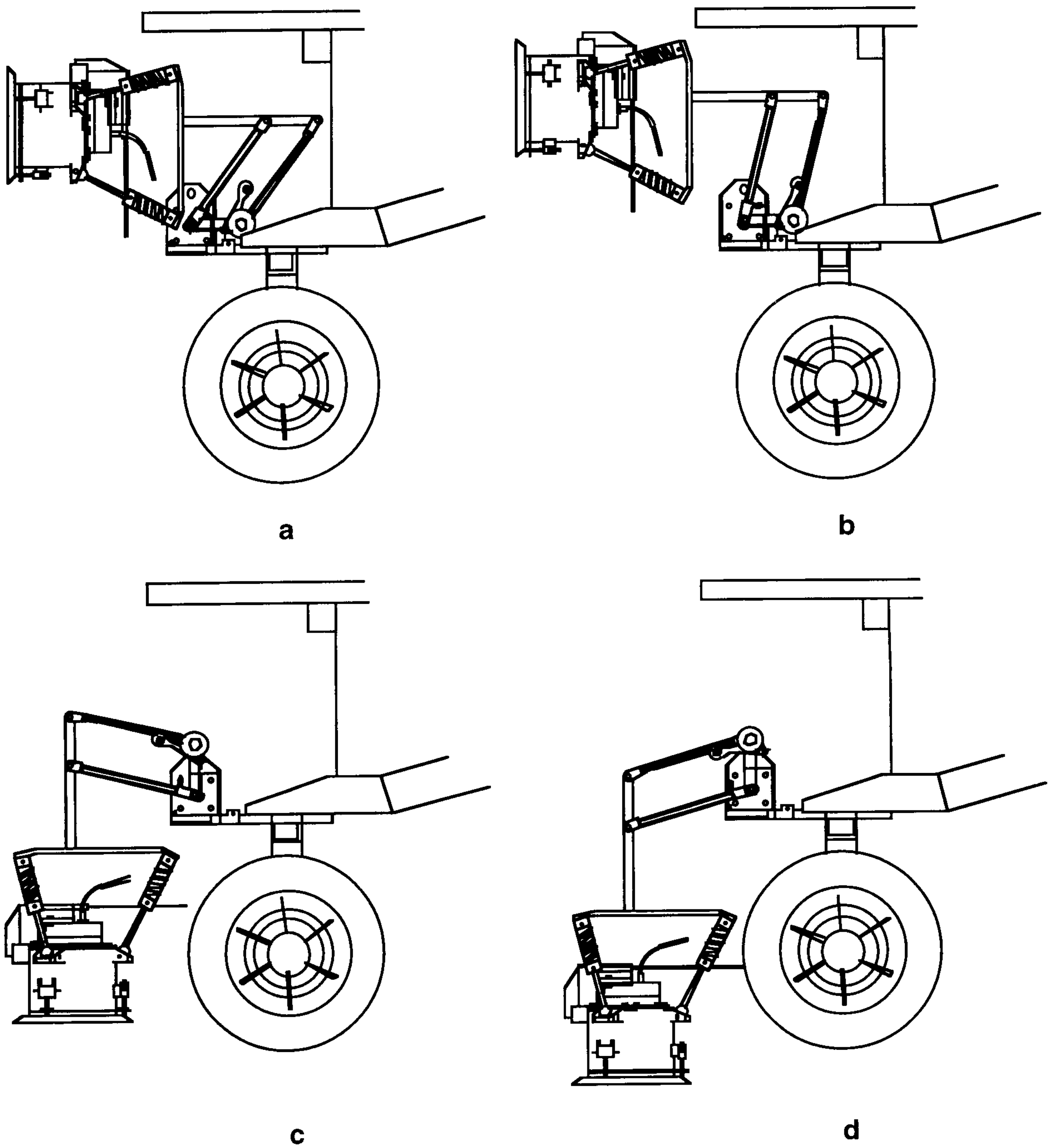


Figure 10. Travel and orientation of the parallel link system: a, stowed position; b, back parallel link contacting stop, horizontal extension stopped; c, links rotated 90°; d, links extended vertically downward.

The details of the parallel link hardware and its workings follow (see parts nomenclature in Figures 11a and 11b). An actuator consisting of a Maxon brush DC motor and a Globe gearbox with a 2000:1 gear ratio drives the front parallel link at its base. A transverse link connects the base of the front link to the base of the back link, and a horizontal link connects the tops of the front and back links. A tab on the transverse link rests on the mechanism shelf. To keep the tab resting on the shelf during the initial horizontal movement of the mechanism, a torsion spring acting between the back link and the transverse link drives the back link toward the front link, resulting in a contact load between the tab and the shelf. As long as the contact load exists, the back parallel link acts as if it were anchored to the shelf.

After the mechanism moves the sensor horizontally, the back link comes in contact with a spring-loaded stop, loaded against the transverse link with another torsion spring. The spring load on the stop is greater than the spring load on the back link, so the mechanism stops extending and the parallel links effectively lock up. As the actuator continues to drive the front link forward, the entire mechanism rotates. After 90° of rotation, the transverse link comes in contact with a hard stop, and rotation ceases. Torque from the actuator then overpowers the spring-loaded stop and the mechanism moves the sensor head vertically down to the soil.

Because the mechanism has only one active degree of freedom, a potentiometer connected to the front link gives all the information needed for the Rover control system to determine the basic configuration of the mechanism. Using the potentiometer, the control system can position the mechanism anywhere along its travel path, while at the same time being aware of the position and nominal angular orientation of the sensor head.

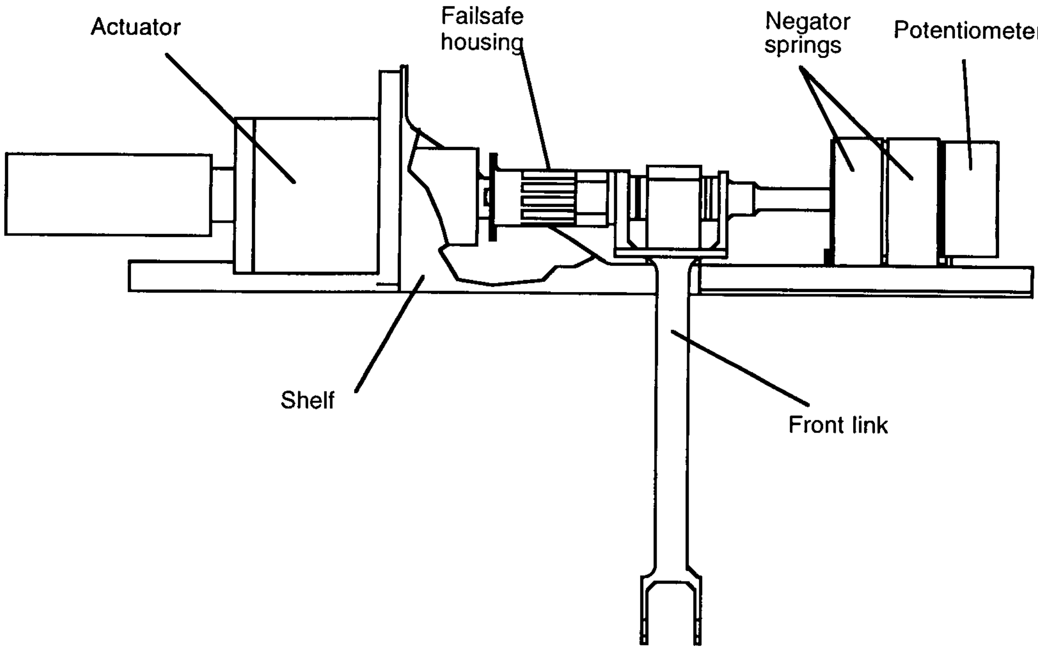


Figure 11a. ADM parts nomenclature: front link base axis.

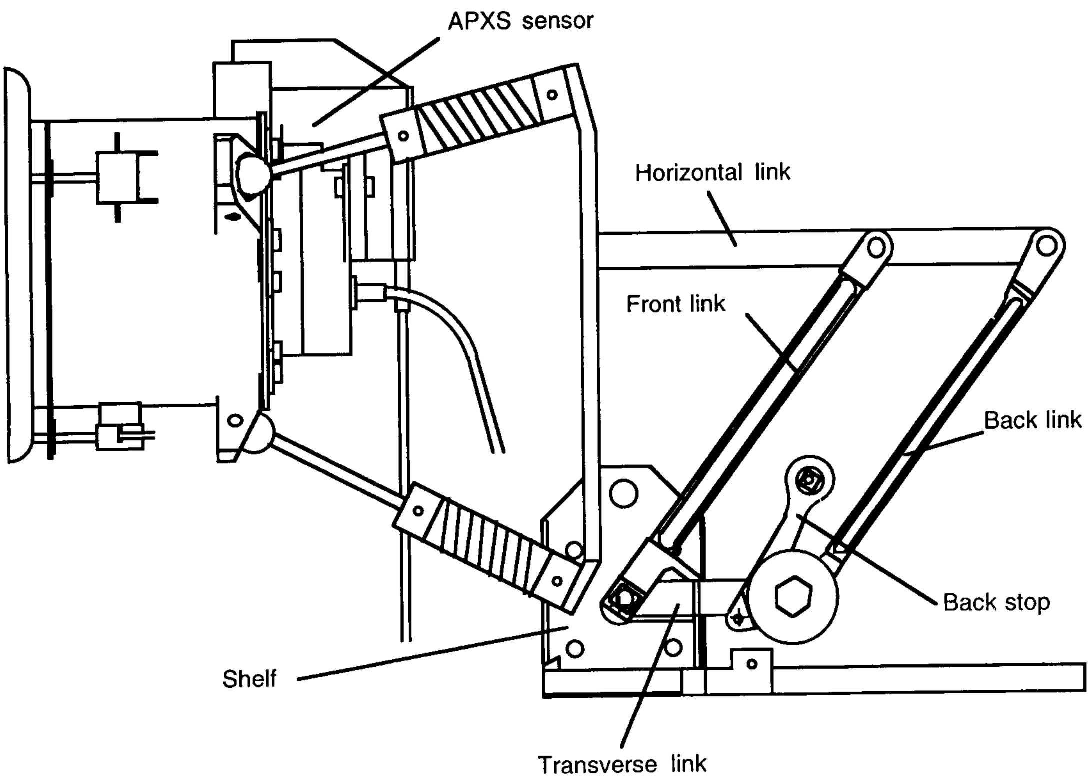
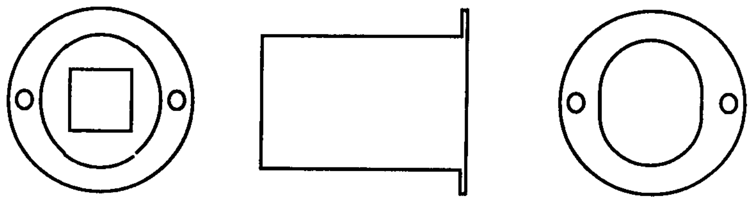


Figure 11b. ADM parts nomenclature: ADM side view, with Negator springs, potentiometer, fail-safe housing, and actuator removed.

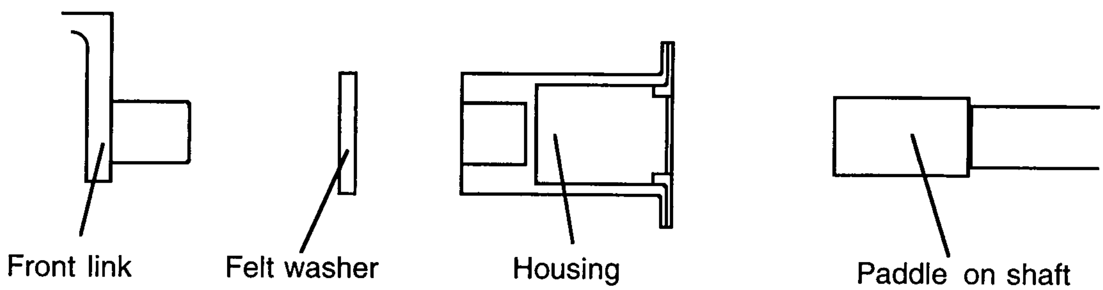
Fail-safe Mechanism

If the actuator fails when the mechanism is in its deployed position, rover clearance is reduced to zero and the rover is crippled. To ensure recovery from a failed actuator , a rotary fail-safe mechanism must be included in the mechanism design. This fail-safe, when actuated, must retract the mechanism fully into its stowed position. It must also provide at least 1.1 N·m of retraction torque, withstand 100 g's and 17 N·m of torque, and survive temperatures from -110° C to +70° C and atmospheric pressures ranging from high vacuum to 101.3 kPa. Furthermore, rover constraints require it to have no pyro firing and use less than 10 Watts for a maximum of 10 minutes when operating in Mars ambient conditions (-100° C and 1.3 kPa CO_2). Finally, the fail-safe mechanism should weigh 0.020 to 0.030 kg, fit into a 0.025 m x 0.050 m x 0.050 m volume, and be inexpensive.

Since pyrotechnics are out of the question, alternative release devices become prime candidates. Among several possibilities are wax pellet actuators, but their size, cost, and power consumption make them prohibitive. Another idea is a nitinol pin puller, with multiple strands pulling on the pin. However, due to friction imposed on the pin, the energy necessary to activate the nitinol wire and maintain adequate pulling margin exceeds the design limit. The final idea consideration is a low-melting-point metal pellet coupler in parallel with a Negator spring pack (see Figure 11a and Figure 12). In its solid state, the metal rigidly connects the driver (the actuator) and the driven part (the mechanism). When commanded, a strip heater wrapped around the coupler housing melts the metal pellet, allowing the driven part to turn independently of the driver. With the pellet melted and the mechanism decoupled, the Negator spring retracts the mechanism to its fully stowed position. This concept meets all the design criteria and provides an added benefit. When the metal rehardens, the coupler once again rigidly connects the actuator and the mechanism as it did before actuation.



Cerrobend housing, side and end views



Exploded, cut-away view of housing mounting

Figure 12. Fail-safe housing.

The concept of a metal alloy coupler originated with a metal in mind, namely Cerrobend. This material typically is used in fusible links such as fire suppression sprinklers and as structural support during machining of thin-walled parts. Cerrobend consists of bizmuth, lead, tin, and cadmium, and melts at 60° C. In its liquid state, it has the consistency and cohesiveness of mercury. In its solid state, it looks like lead and has a shear strength of around 25 MPa.

Because a strip heater wraps around the outside of the coupler, the Cerrobend pellet housing has to be thermally conductive. Yet, it must be able to withstand 17 N·m of torque when filled with Cerrobend. Its shape should also keep the Cerrobend pellet from turning inside and from deforming under load. A cylindrical shape is inadequate, as the shear strength between the pellet and the housing wall is insufficient to keep the pellet from rotating . An aluminum housing with an elliptical shape and 0.0004 m thick wall, however, is thermally conductive, prevents the Cerrobend pellet from turning even under high loads and is strong enough to survive 17 N·m of torque.

The elliptical shape also makes it easier to effectively mount a strip heater around the coupler housing using RTV66, a silicone adhesive rated for cold temperature use. Although RTV66 is not an excellent conductor, it is used because only a very thin layer is required for adequate bonding. As an added safety feature, shrink wrap placed over the strip heater redundantly keeps the heater in place.

The end of the drive shaft is shaped like a paddle to increase shear area between the driver and the Cerrobend. This configuration provides enough area to meet the design criteria, even though the shear strength of Cerrobend is only around 25 MPa.

To more fully thermally isolate the coupler, the drive shaft, the drive paddle, and the front link are all made of titanium, because of its low thermal conductance. A felt spacer between the coupler and the front link provides added thermal conduction isolation and a felt booty wrapped around the coupler housing virtually eliminates convective and radiative losses in the coupler.

The concept presented here can easily be applied to other applications where release devices are needed. For example, spring-loaded pin puller/pusher devices can use Cerrobend pellets to hold the pins in place before actuation. Also, electrical disconnect mechanisms can disconnect wires via a spring-loaded Cerrobend spreader. The issues to be concerned with are thermal isolation, proper setting of the parts before actuation, and possible outgassing concerns. However, when these issues are overcome, the resulting release mechanism can promise to be the most light, simple, power-conserving alternative available.

Launch Configuration

Tying the mechanism down during launch, descent and landing is the last great technical obstacle. The optimal approach is to hold the sensor down to the rover and eliminate any direct tie to the lander. However, such a stowage device is too heavy for the rover to carry. Taking advantage of the compliance of the mechanism, the sensor is instead pulled down to the lander mounting surface and held in a launch support saddle with a cable, as shown in Figure 13. The helical springs in the wrist attenuate rover/lander load transfer through the mechanism.

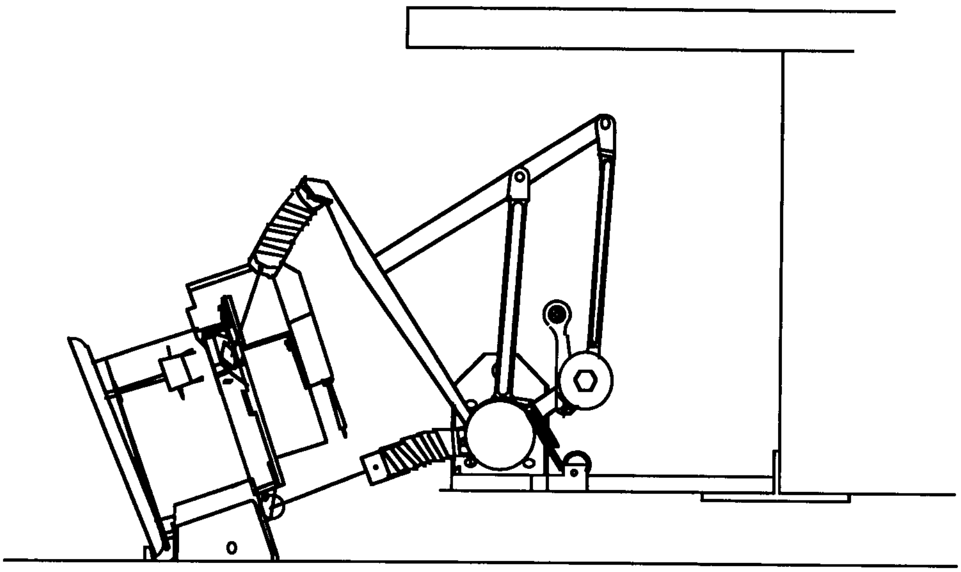


Figure 13. ADM launch stow configuration.

TESTING

A barrage of tests performed on the ADM prototype validate the design. These tests include the following:

- Flexible wrist compliance force and stability
- Bumper assembly functional tests
- Parallel link functional tests
- Actuator characterization tests from room temperature down to -100° C
- Full-up functional and torque margin tests at Earth and Mars ambient conditions
- Fail-safe actuation tests at Earth and Mars ambient conditions

Other tests scheduled for the flight and spare units in February and March of 1995 include all the above plus:

- Vibration and static load tests
- Thermal vacuum tests
- Thermal cycling tests
- Contamination tests
- Post-environmental functional and margin tests

The parts underwent a stress analysis using ADAMS, a dynamic simulation program, and COSMOS, an FEA package. Although the predicted flight loads are less than 70 g's, the hardware is designed to withstand greater than 100 g's.

Some of the detailed results of the prototype testing are listed below and provide an idea of the capability of this hardware.

Wrist Compliance Force

The force required to tip the sensor head 25° varies from 1.38 N to 2.45 N. This variance is due to the location of the applied force. If the force acts in the location of a spring-mounted support rod, less force is necessary, as one spring contributes most of the alignment resistance. If the force acts in the area between support rods, then two springs together provide the majority of alignment resistance.

When 4.9 N of force is applied, the three support rods of the flexible wrist may rapidly twist around the sensor head. This instability phenomenon occurs only when the approach is straight-on. Although it typically does not affect sensor head alignment, 4.9 N does act as an upper limit for flight operation, in that the hardware alignment indication system is designed to give alignment indication before the force on the sensor reaches 4.9 N

Alignment Indication

The bumper requires less than 4.9N to compress all three plungers and 1.35 to 2.2 N of force to compress just one. This is almost the same as the force required for maximum wrist compliance, so the bumper will indeed compress only after the flexible wrist aligns the sensor head to the best of its capability.

Torque Required

Measurements of the torque required for deployment and retraction are shown in Figure 14 below.

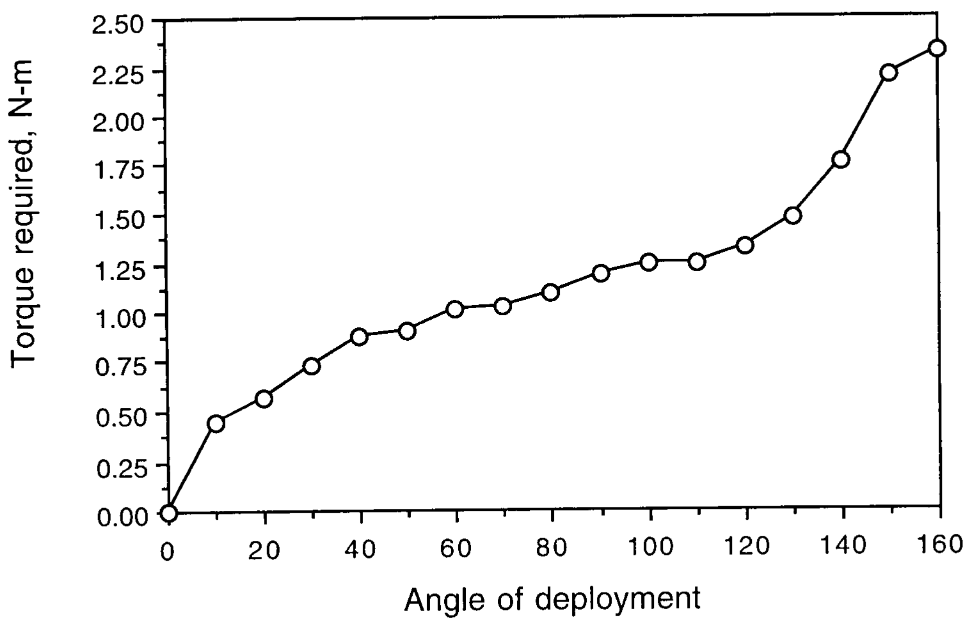


Figure 14. ADM torque required to deploy.

Actuator Tests

From results of the actuator characterization tests, the actuator has the following operating characteristics:

Free-running speed	1.2 rpm
Working load speed (1.0 N·m)	0.6 rpm
Back-driveability	4.0 N·m
Stall torque	4.5 N·m at 23° C, up to 11 N·m at -100° C

This translates into a minimum torque margin of 0.88 at 23° C and 3.58 at -100° C. The rise in actuator capability at cold temperatures is due to lower electrical resistance and only a very small increase in drag in the actuator.

The prototype actuator design did survive preliminary vibration tests and operating temperatures as low as -116° C without any noticeable side effects.

Fail-safe Operation

Testing results show that in a Martian environment of -95° C and 1.3 kPa CO_2 atmosphere, the 0.01 m x 0.0125 m x 0.02 m fail-safe coupling takes approximately five minutes to actuate when 6.75 Watts of power are provided. A graph of typical temperature vs heating time is shown in Figure 15. In these cold conditions, the fail-safe coupler melts gradually, resulting in a slow, benign retraction of the mechanism.

The operating equilibrium temperature, represented by the asymptote of the graph, appears to be 70° C, only 10° higher than the melting temperature. The low margin is a result of the lack of felt insulation around the coupler housing. Addition of a felt washer and a felt booty as previously described in the mechanism description will increase the margin.

Torque tests at Earth ambient conditions indicate that the fail-safe coupler can withstand more than 17 N·m of torque with no slipping. However, multiple actuations of the fail-safe mechanism cause the withholding torque and actuation time to both decrease, due to incomplete melting of the Cerrobend around the drive shaft. This is attributed to the shape of the paddle. In the prototype, the cross-section of the paddle had the shape of a plus sign (+). The Cerrobend did not melt sufficiently in the corners of the paddle before the fail-safe retracted. During resolidification, discontinuities appeared, causing the torque holding capability and actuation time to decrease.

To ameliorate the problem, the paddle was changed to a flat, oar-like shape, as shown in Figure 12.

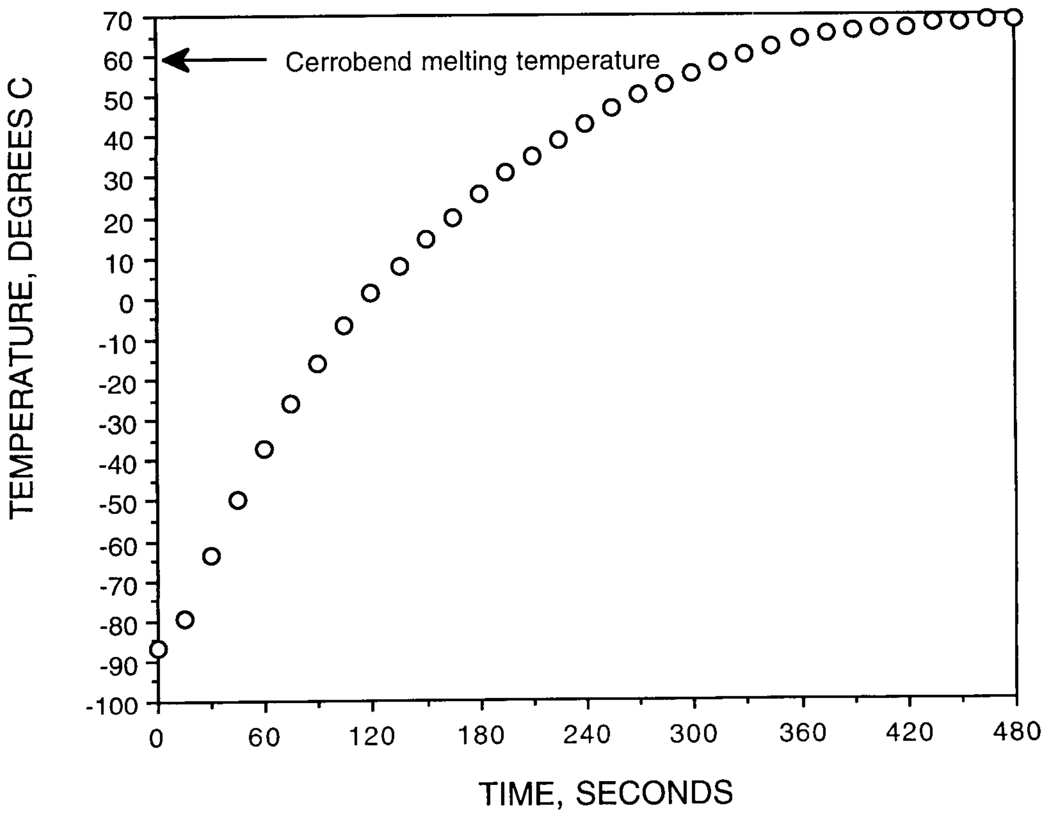


Figure 15. Typical Temperature vs time graph for Cerrobend fail-safe coupler.

CONCLUSIONS

Functional tests of the prototype unit indicate that the hardware meets its requirements. Environmental tests for the flight and spare units are not yet done, so full validation of the design will have to wait until March of 1995. However, analyses verify that the hardware will pass these tests, too.

The ADM is an amalgamation of unique solutions to challenging design problems. The resulting design is light, flexible, and nearly autonomous. Its straightforward operation rivals that of a human arm in simplicity and elegance. Its successful operation will greatly contribute to the cornucopia of useful information gleaned from the Mars Pathfinder mission.

The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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1. Nevins, James L. & Whitney, Daniel E., "Computer-controlled Assembly", Scientific American, February, 1978, pgs 62-74.