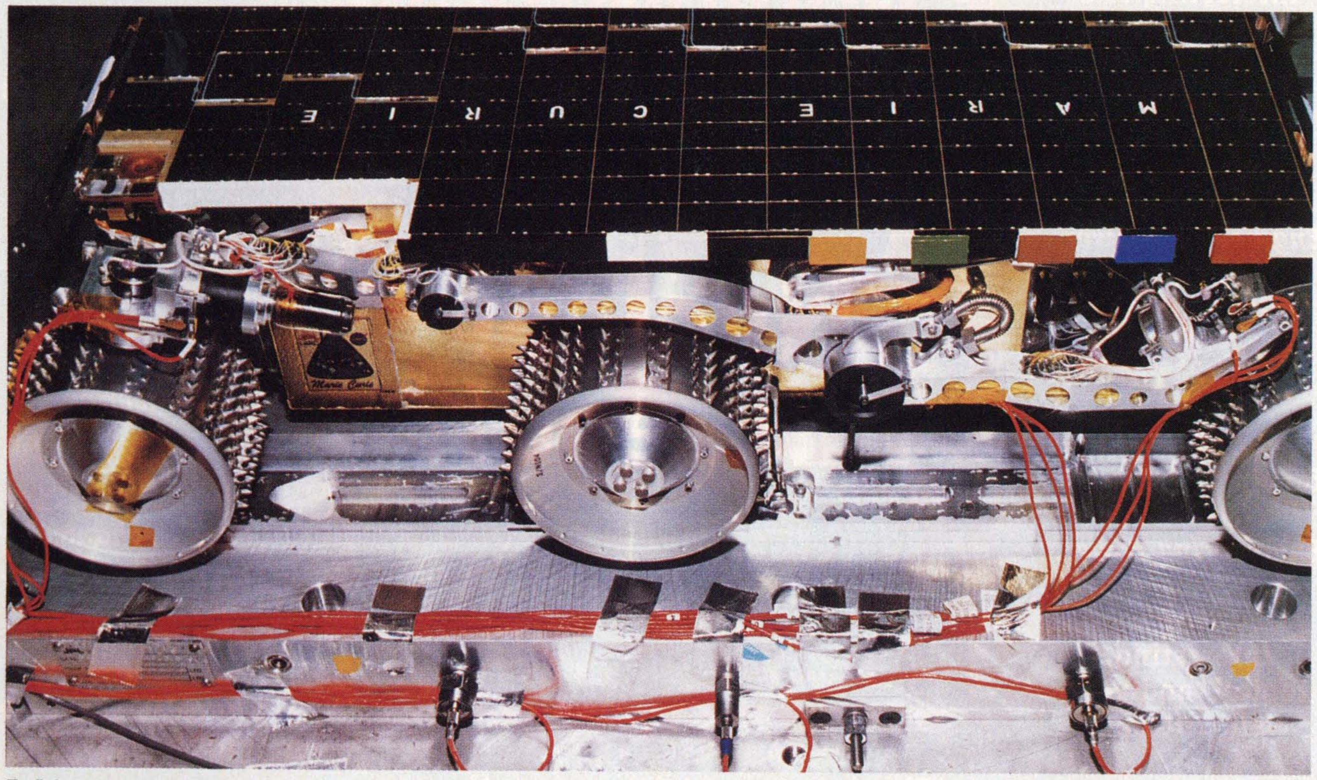
Roving over Mars

Operating nearly 125 million miles from home, the Sojourner rover had to be very reliable and highly mobile to forge a path along the Martian surface. **By Donald Bickler**



To fit in a small space aboard Pathfinder on its trip to Mars, the rover must squat down by breaking the rocker links where they pivot on the body. The locking spring that will enable the Sojourner rover to reach its full operational height is shown in the bent position.

SHROUDED IN AIR BAGS that formed its landing system, the Mars Pathfinder hit the surface of the Red Planet—hard—on July 4, 1997. Some 90 minutes after bouncing around and finally coming to rest, the craft removed its cocoon to reveal a lander and the Sojourner rover vehicle. Back on Earth, millions of people tuned in to watch the rover's exploration of another world on television and World Wide Web sites dedicated to the mission.

The Pathfinder lander and Sojourner have completed their successful mission. During its three months of travels—12 times longer than the vehicle was designed to last—the rover explored the vicinity of the lander in the Ares Planitia, probing the Martian surface and photographing its rocky environs. It analyzed the chemical makeup of the soil and various rocks. It dug into the surface, measuring soil strength and the abrasive characteristics. The 630-millimeter-long, 10.5-kilogram Sojourner has done all that was expected of it and more, paving the way for future missions to Mars.

In designing the vehicle's mobility system to handle the harsh Martian surface, engineers at the Jet Propulsion Laboratory (JPL) in Pasadena, Calif., had to provide it with a mobility far in excess of conventional all-terrain vehicles. Because command signals from Earth would

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take more than 11 minutes to travel the 123.5 million miles when the probe landed, Sojourner had to be a semiautonomous vehicle that would not need servicing. That reliability involved more than just not breaking down: The device also had to be able to negotiate the terrain without getting jammed or hung up. At the design stage, this involved the planet's actual makeup and any potentially hazardous situations that might occur. For example, the design took into account smooth, glassy volcanic rock with little or no friction and talcum-powder-like dust at depths greater than the vehicle height. To our delight, the rover never encountered these hazards; the vehicle was overdesigned because we didn't know exactly what we would be up against, but this helped the vehicle last so long.

Spider Legs and Wheels

In the 1980s, well before the Sojourner design was chosen, contractors to JPL performed numerous studies regarding the various types of vehicle configurations. One proposal involved very complex legged designs intended to climb and leap like spiders and mountain goats. We all wanted to work on the challenging mechanical problems involved with such designs, but the control problems were overwhelming. In addition, having the device "see" ahead and plan foot placement proved very difficult. Another option was simple legged vehicles. These variations on the walkers used by the physically impaired place one set of feet forward as they stand stably on another set. Weight is then transferred to the forward set to form a new stable configuration, and the process is repeated. With three legs, however, the vehicle tips easily; more legs than that and it teeters. Also, the simple legged design cannot be set on a rock, is a problem to steer, and limits instrument access to rock faces.

On the basis of simplicity, efficiency, light weight, and ease of control, a wheeled vehicle was chosen. Four-wheeled vehicles would be the ideal choice using these criteria, but they do not climb obstacles very well, especially obstacles that are larger than the diameter of the wheels. A configuration with a wheel base equal to three-and-a-half wheel diameters and a center of gravity midway between the wheels can be used as an example. If we place a vertical wall in front of both front wheels of such a vehicle, the front will rise when the coefficient of friction is 0.778 or greater. The bottom of the rear wheel drives at ground level and the wall resists at axle height. This results in a moment that lifts the front. The friction at the front raises the vehicle with a moment arm equal to the wheel base plus the radius of the front wheel. The center of gravity resists with a moment arm equal to half the wheel base.

When the wall is placed in front of the rear wheel, the coefficient of friction required becomes 1.4 or greater. The wall reacts at axle height and the front wheel pulls at ground level, resulting in another moment that tends to lift the front. The friction at the rear raises the vehicle with a moment arm equal to half the wheel base minus the rear-wheel radius. The center of gravity continues to resist with a moment arm of half the wheel base minus the radius.

By increasing the complexity 50 percent—in other words, by adding two wheels—a vehicle can climb vertical walls on both sides when the coefficient of friction is 0.8. The six-wheeled Sojourner rover can climb in the forward direction with coefficients of 0.5, 0.68, and 0.6 for the three wheel positions in order, and in reverse with coefficients of 0.78, 0.75, and 0.82. (Eight wheels would perform even better, but the added complexity and associated steering problems make the vehicle impractical.) Six wheels are better than four because when two wheels are climbing over a rock, say, they get pushed against it by the other four. This results in more climbing traction; at the same time, a lesser fraction of the weight is being lifted.

To increase traction even more, the wheels have cleats that protrude 10 millimeters and dig into the sand. Formed from 0.127-millimeter-thick stainless steel, these rather sharp cleats will grip on the slightest irregularity. This feature helps the rover climb right up the face of a rock, but it also complicates the autonomous navigation by changing the effective rolling radius over both soft and hard surfaces, a problem that was not fully overcome.

The flexibility of the mobility system enabled Sojourner to explore the surface and investigate rocks such as Yogi, which appeared to be similar to common basalt found on Earth.

The 79-millimeter-wide wheels enable the rover to "float" over the Martian surface. They sink to their design depth for soft material with a ground pressure of only 1.65 kilopascals. (A low ground-pressure requirement means the vehicle can traverse very soft soil.) This is far less than the average ground pressure for an automobile, with approximately 240 kilopascals, and an Army tank, with 48. Conditions on Mars never required such a low pressure, however, because the ground was never that soft.

Obstacles to Overcome

The ability to climb obstacles is not primarily a function of the wheels, however, but of the rover's suspension system. The system's unique configuration, which has been developed over the last several years, is known as the rocker-bogie system because the front and center wheels are joined on each side to form bogies. These bogies pivot freely at the front of rocker links. The rockers each have a rear wheel at the other end, and are pivoted freely at a point near their middle. These pivots are where the body attaches.

The body is controlled in the pitch direction by a set of links that form a differential, keeping the body at an average angle between the two rockers. The system has no springs or intentionally elastic members, which improves Sojourner's traction. When a wheel is suspended with an elastic system, the downward force increases as the wheel is raised according to the spring rate of the system. The greater force makes it more difficult to raise the wheel as it takes downward force away from the remaining wheels, reducing their traction.

Stability is key to the vehicle's overall effectiveness. This includes the ability to stop at any point and proceed or reverse, even while climbing a vertical wall. For this reason, the first analyses were done to optimize the ability to climb vertical bumps that are axle-high or larger. Bumps are obstacles that fit between the wheels, so that all wheels not climbing are on a single plane. Steps, which carry the vehicle from one level to another, represent another type of obstacle. Climbing steps is easier than climbing bumps, because the rear wheels are hoisted by the rest of the vehicle; also, the lifting force is downward on the wheels on the step, increasing their traction. Bumps, on the other hand, cause the forward wheels to be dragged backwards as the rear climbs. The downward force of the climbing wheel in this case tends to lift the forward wheels, reducing traction. This difficulty had to be overcome since bumps are common on Mars and steps are rare.

Sojourner spent three months traveling over Mars, 12 times longer than originally designed.

The process of optimization began by solving for the coefficient of friction needed to climb vertical surfaces at each of six positions (in front of and behind each pair of wheels, front center, and rear). This made it a two-dimensional problem by taking both sides of the vehicle up the obstacle at once (it is considerably less difficult to climb an obstacle on one side only). A seventh position was added later to analyze the four-wheeled situation in which the rover "pops a wheelie," raising the front wheel(s) because of resistance at the rear. The linkage proportions were traded—changed in a given direction so as to favor one wheel over another—in a way to minimize the limiting coefficient of friction. We later changed the front of the bogie link, lengthening it so the front wheels can back out easier. This configuration was compared with the results of other analyses, which solved for the steepest angle that can be climbed when the coefficients of friction are known.

In this set of analyses, the coefficient of friction was different on the horizontal than on the obstacle. The most popular set was a coefficient of 0.8 on the obstacle and 0.3 on the horizontal, for climbing rocks in sand. All of these analyses assumed unlimited torque at every wheel. This assumption allows the wheel traction to be limited by the soil friction coefficient only. The actual flight design has more than enough torque to turn the wheels under the most severe conditions. In fact, it has so much torque that it is capable of a tangential force on each wheel equal to half the weight of the entire vehicle on Earth.

The rover can easily climb obstacles that are more than 30 percent of its length. These obstacles can be overrun both straight on and while turning at will. By comparison, the average family sedan could drive unconstrained over obstacles measuring 1.5 meters.

Steering the Martian Way

Climbing is not the only function of JPL's rover mobility system; steering is just as important. The final rover design steers the wheels at all four corners, and each of those wheels has an independent steering system. The vehicle performs well in a crabbing maneuver—when the vehicle moves sideways like a crab—even though the center wheels aim forward. With all four corner wheels aimed diagonally to one side, the center wheels scuff sideways, contributing only forward thrust. As the vehicle crabs, it moves to the side without changing heading. On Mars, Sojourner was able to perform this maneuver successfully to sidestep obstacles.

Experimental models were made with all six wheels steerable, which allowed crabbing without scuffing and increased versatility. This would improve the ability to crab as the rover climbed obstacles. Better versatility would also raise weight, cost, and volume of the increase from the additional steering motors and gearboxes, so such a design was vetoed.

Normal steering requires the axes of all wheels to coincide at a single point, a geometry called Ackerman. The single point is the center of rotation. Because each wheel is steered independently, this center can be situated anywhere along the centerline of the middle wheels. When the wheels are turned in a crossways manner (the right front wheel is turned to the left, the left front to the right, and so on), this center of rotation can be at the vehicle's center. This turns out to be the most popular maneuver because the navigation system does not have to calculate a new position for a change in direction. In fact, after Sojourner backed down the lander's ramp, its first such maneuver was to rotate in place, so the rover could turn without losing the known position. Sojourner frequently performed this move to turn and climb rocks at the same time.

The ability to clear rocks and other obstacles, rather than just going over them, is also an important aspect of design not only for Sojourner but for any all-terrain vehicle as well. The ground clearance is set at one-and-a-half wheel diameters. Should the rover initially clear an object but then get stuck while going over it, the body's belly pan can support the vehicle's entire weight. This belly pan is considered part of the mobility system.

Once on Mars, the rover climbed obstacles as efficiently as our field tests and calculations predicted. The big unknown was encountering a soil type we were not familiar with, but Martian soil appears to be very similar to that on Earth.

ABOARD PATHFINDER

Once the specific six-wheel configuration was chosen, JPL engineers had to make the vehicle squat down so it would fit economically onboard Pathfinder for the trip to Mars. Originally, the plan was for the rover to be on the base petal of the lander and straddle some of the electronics under its body in the ground-clearance space. In the final Pathfinder design, however, the rover had to be mounted to a side panel where it only straddles the lander's solar cells.

To fit in that small space, the vehicle squats down by "breaking" the rocker links where they pivot on the body. The rover later stands up by driving the rear wheels forward with the remaining wheels locked. After the rocker links are arched to their full height, a mechanism on each side snaps into place, locking them into position forever. This mechanism is a coil spring tightly wound to its solid height and bent over to where the opposite ends almost touch when the rover is down.

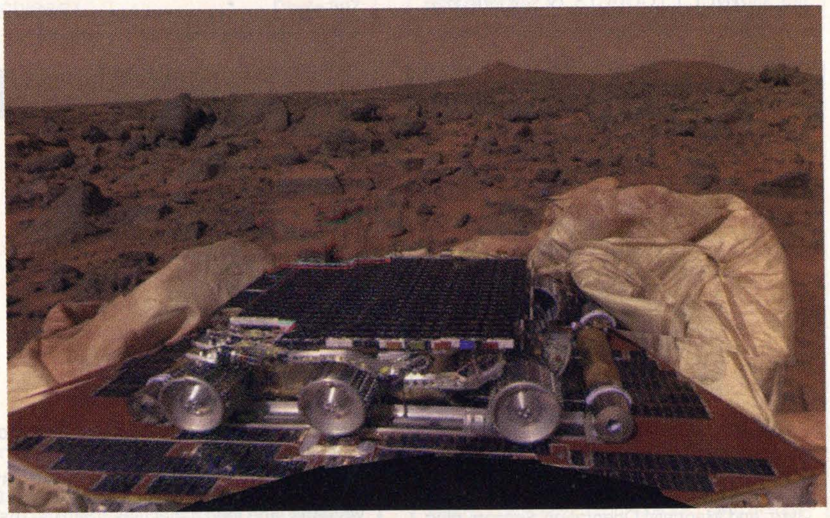
After full height is reached, the spring snaps straight to become a ridged compression member. The differential is active in the standing-up process, and keeps the body parallel to the panel as it stands. To do this, the differential arm on the rocker is joined to the front of the right side and to the rear of the left side. With the vehicle folded, the differential behaves as if a very large obstacle is at the right front and another at the left rear. As the vehicle stands, both these obstacle angles decrease and the differential keeps the body parallel to the point where it locks in place. To pull this off, the rocker links must be broken at a point where the front and the back parts rotate through the same angle, which involved putting a kink in the front half of each rocker link to clear the center wheel when folded. Because the rover can stand up without tipping, the instruments on each end are not smashed against the lander bed.

THE COST OF COLD DAYS

Another key design factor was the Martian temperature: On the afternoon of July 30, for example, temperatures reached a balmy −13°C, and the forecasted low for the next day was −73°C. We designed the rover for a cold winter night of −100°C. Sojourner's batteries and electronics, for example, are in a high-tech aerogel-insulated, fiber-reinforced-plastic composite body heated by three radioisotope heating units. Dry lubricants prevent the vehicle being pasted with congealing oil. The wheels drives use ball bearings with plastic balls, aluminum races, and no lubrication. An X-type bearing design, large enough for the motor and gears to fit inside, takes all wheel loads and the final stage of the planetary gearing. This type of bearing takes radial, axial, and moment loads, all with a single row of balls.

Furthermore, joints had be designed to accommodate the differential expansion over the temperature extremes. In addition, the motors have heaters on them because some lubricant had to be used on the commutators. These motor heaters were not used, so they proved to be another example of Martian overkill.

One key element of Sojourner's design had nothing to do with the environment on Mars but everything with



With Pathfinder's air-bag cocoon removed, its "petals" are unfurled to expose Sojourner to the Martian air. Scientists used this image to decide whether ramps for the rover could be deployed.

the financial climate back home: maintaining low costs. Mars Pathfinder is part of NASA's Discovery Program, an initiative for planetary missions with a maximum three-year development cycle and a cost cap of $150 million (in 1992 dollars) for development. To this end, the motors and gears are slightly modified, off-the-shelf commercial products. In addition, the rover is the fifth generation of an idea from the 1980s; the first four generations were funded as research and development. This cut down on engineering costs, which are greater than hardware costs.

The success of Sojourner's mission means that more rovers will be used in the future to carry scientific instruments to other sites on Mars. What we learned in designing this rover's mobility system will be applied to other missions, such as for the Mars Surveyor 2001 mission. Other rovers may someday be large enough to carry manned missions and nonrobotic drivers. By designing these reliable, highly mobile planetary rovers, we can expand the reach and scientific value of exploratory missions to other worlds. ▪

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