The Retelling of

"Romancing the Rover (How Sojourner Came to Be in the Late 1980s and Its Journey to Mars)"

JPL Stories, September 28, 2000

Presenter: Don Bickler

Reteller: Marilyn Morgan with Don Bickler

The sixth in the Library's series of JPL Stories attracted a roomful of enthusiasts, including some of the presenter's team members "to see," he asserted, "if I make a mistake." The room buzzed with anticipation, and even before Don Bickler began his talk, we could perceive a familiar JPL gestalt — the energetic demeanor, the ebullient manner, the general look of someone who is about to share something that is really terrifically exciting.

Sojourner had gone to Mars, fulfilled all expectations, captured the public imagination, even became a toy, and finally emerged as an icon of JPL ingenuity. We were about to hear from someone who was present at the creation — and not only that, he was wielding the wrench and screwdriver.

I'm convinced that engineers, despite their sober and serious reputation, have just about all the fun there is to be had in the world. They grab onto a problem and address, define, analyze, and solve it intellectually. That's exhilarating in itself, but then they get to *build things*: structures, bridges, vehicles, rockets. Rocketry engineers have even more fun: they get to build things and then fire them into the sky or (accidentally of course) blow them up. If you have seen the old films of Robert Goddard and his crew jubilantly experimenting with liquid-fueled rockets in the New Mexico desert, you know what I'm talking about.

Engineers who build robotic vehicles also have a bit of that maniacal gleam in the eye. They experience the joyfulness of creating things that scurry, scoot, roll, reach, climb, scramble, pivot, and peregrinate, while carrying out instructions on command or, even better, these neoteric critters decide things on their own through software created by their human designers. Like symphonies, sophisticated robots are art forms. But the robots that seem to operate so easily and beautifully are not born so much as bred, through generations of robots, some of which never get beyond the drawing board, and some of which are magnificent failures. Sojourner, which seems the perfect realization of a compact robotic rover, evolved at JPL over quite a few years. Her distant lumbering ancestor is the Surface Lunar Roving Vehicle, circa 1967.

The Bogie Man

Don Bickler was introduced by Barbara Amago of the JPL Library storytelling team. We learned that Don graduated from Northwestern University in 1956 with a degree in mechanical engineering, and eventually ended up at JPL in 1975. He is now supervisor of the Advanced Mechanical Systems Group in the Mechanical Engineering Section (352). Bickler's invention of the rocker-bogie suspension system earned him a nickname — The Bogie Man.

(An aside — According to the Oxford English Dictionary, a golfing "bogey" derives from a popular 1899 song describing a dreaded person, devil, or goblin, but a mechanical "bogie" originated in 19th-century northern English dialect, describing a low truck on four small wheels used by masons to move large stones. Eventually "bogie" came to describe a truck running on two or more pairs of wheels supporting the forepart of a locomotive engine on which it swivels freely in passing curves.)

Rough-Terrain Vehicles

A before-talk exchange between Don and an audience member confirmed that the bogie design is commonly used in tandem-wheeled trucks, military trucks, and cranes to provide stability and mobility on uneven terrain. Could Sojourner, so refined looking, be related to these rough characters?

In the 1960s, we were told, the military developed several types of articulated vehicles. Don showed photographs of these strange vehicles, including a six-wheeled "bent jeep" that was supposed to be able to climb over low obstacles, and the Lockheed Twister, bearing the appearance of several vehicles in a state of post-collision. Another, the sturdy-looking Gamma Goat, was classed as a 1-1/2-ton truck and sported articulated six-wheel drive. All these were designed to traverse rough terrain such as might be encountered in war-fighting situations or military logistical enterprises. Early rover designers studied these types of vehicles for clues to creating mobile machines that would be successful in planetary excursions.

Lunar and Planetary Roving Vehicles

Sojourner's pedigree begins with a Surface Lunar Roving Vehicle (SLRV) delivered to JPL about 1967. The segmented vehicle was supposed to fold up into an "S" shape, and could climb obstacles 1.5 times its wheel diameter. The SLRV was never launched, but provided a study object for early JPL rover engineers. The vehicle was invented by Mieczyslaw G. Bekker, whose team designed the Lunar Roving Vehicle used in the Apollo 15, 16, and 17 missions (1971–1972). Bekker's first book on the theory of land locomotion and terrain–vehicle interactions ("terramechanics") was published in 1956, and by 1963 he was proposing Moon rover designs. Bekker tried lots of things in his designs, including variations on Archimedes' screw.

In those days — the heady Apollo days — NASA was thinking big, and cost was not a problem. The Apollo LRV was about 10 feet long by 6 feet wide (to wheel centers). Each spring-steel, wire-mesh wheel was driven by a 1/4-hp electric motor, and the front and rear wheels had separate steering systems. Either of the front or rear wheels could be turned while the other pair was locked straight, or both could be used simultaneously, so the rover could turn completely around within its own length. It could climb over obstacles 1 foot high and negotiate 25-degree slopes. All these were desirable characteristics in a roving vehicle. Additionally, the Apollo LRV had to fit into the Lunar Descent Module — for stowage, all four wheels folded inward and the vehicle folded double — and be easily deployed on arrival.

Another idea for a lunar rover was the MOLAB or mobile laboratory: a 3-ton, closed-cabin vehicle with a range of about 100 kilometers. The MOLAB was an articulated vehicle with independent suspension and 1.5-meter-diameter wheels, but was far too large for what NASA ultimately required for Apollo.

Big Mars Rover Concepts

In the 1980s, interest in Mars spurred new thinking at JPL about what we would want in a robotic rover, should the opportunity arise for a journey. The SLRV, the baseline vehicle, morphed into the Little Blue Rover. The Blue Rover had an elastic (spring) chassis and could clamber over 1-1/2-wheel-diameter obstacles. Don showed us a vintage-1986 drawing of a rover concept that illustrated a six-wheeled articulated vehicle of three sections: a forward portion with two science-instrument arms, a middle portion with camera, and an aft portion that seemed to be solely RTGs on two wheels. (The shape of the vehicle wheels resembled narrow automobile tires, and this became an issue when different types of terrain were considered.) Bickler began thinking about bogie linkages to overcome the undesirable characteristics of using springs.

The next illustration Don showed us was "Fig. 3" from his 1989 patent (no. 4,840,394) for an articulated, springless suspension that maintains uniform distribution of weight and traction on the wheels. Fig. 3 showed a six-wheeled vehicle with front and rear linkages coupling the front and rear wheels to the middle wheel. It was assumed that equal weight on each wheel is best, but the trick was to make three linkages work ("like clapping with three hands"). The design has a master link on each side, but there was a problem — you can't steer the wheels. The next drawing was a wire frame of a six-wheeled vehicle based on a pantograph design. (A pantograph is the drawing instrument made of four rigid bars joined in parallelogram form to maintain scale while copying a drawing.) The linkages allow steerable struts. Now we're getting somewhere.

In a JPL review discussing rover designs, a CAD of the pantograph design drew pointed criticism from John Casani — "too complicated," "we don't know if it will work," and "why not four wheels?" That shout from the back of the room was Bickler's: "How about a model?!" Don's 1/8-scale table-top model for the pantograph was favorably received at the next review.

In the search for balance among the trade-offs, considerations of weight on the wheels, size of the wheels, number of wheels, type of wheels, steering and articulation, surface speed, ground clearance, and how high the vehicle could climb (size of the obstacle to overcome) were all part of the picture. Four wheels were not enough; six was the optimum number of wheels for stability and obstacle-crossing capability. The idea was that a rover would have to be able to climb over obstacles 1.5 meters high — almost 5 feet. Objects of this size could be seen from orbit. Don's photograph of a person holding a 1.5-meter-long measuring stick showed us that such a rover would have to be really large, and indeed, the next photo showed an experimenter in the east Mojave Desert, standing, for scale, next to wheels of the requisite size: huge, 1-meter wheels on a single axis. These experimental wheels were narrow in shape. Wheel shape is something to think about; you don't want your rover to start off on a Martian traverse and get ignominiously stuck in a ravine into which the wheels precisely fall. Don recalled riding a bicycle as a kid in Chicago along streetcar tracks and realizing that "if you get stuck in the tracks, you're dead." This insight, he declared, "really made an impression on me."

And now, Don said, "everybody tried to get into the act" — from universities to the Russians, the race was on to build the best rover. To climb a 1.5-meter obstacle, inflatable segmented tires or cone-shaped wheels were considered. But venting and pumping inflatables is not desirable in the thin Martian atmosphere, cone-shaped wheels gyrate, and eggbeater-shaped wheels deteriorate and are "too wiggly." JPL's 1990 Robby Rover was a six-wheeled, rubber-tired, articulated rover testbed 13 feet long by 6.5 feet wide, resembling an oversized toy model of a Monster Truck — hardly the sleek, efficient design we would hope for. Robby was also encumbered with a multibody design. Multiple bodies require connecting cables: a key thermal issue is trying to keep several bodies warm. As Don remarked, "the thermal world is a big one" — a whole overlay of engineering trade space.

Little Rovers and Linkages

JPL was starting to envision small, cost-efficient, capable rovers for planetary missions. But the pantograph design, Don decided, had too many links. What was desired was a stable platform, no springs, and a single body. The challenge was to accomplish this with fewer links. The JPL family of vehicles has these features in common (the list from Don's viewgraph):

- There are no springs or elastic members other than those used with the tires.
- There is a single rigid body.
- The rover has very high ground clearance.
- All wheels are capable of being steered.
- The body is differentially connected between the left and right sides on a transverse (pitch axis) shaft.

The question to be answered through the engineers' art was — How simple can it be made and still have the desired performance?

M.G. Bekker — whose name became associated with the Apollo lunar roving vehicles — mentioned a series of equations in his 1969 book, *Introduction to Terrain–Vehicle Systems*. The equations, representing the behavior of wheels over obstacles, had been developed by one Frederick Jindra. Jindra had written a paper that appeared in the "Journal of Terramechanics" in 1966, wherein he showed that it is "easier" for a six-wheeled tractor-trailer vehicle to negotiate a *step* compared with negotiating a *bump*. (In this scenario, the tractor has one set of wheels at the front and one set at the rear; the trailer, hitched to the tractor, has one set of wheels at its rear.) A step is defined as a rectangular object that raises the entire vehicle, whereas bumps can fit in between the wheels. As the trailer is pulled by the tractor, the trailer's wheels rise vertically in attempting to negotiate the bump. But the trailer's wheels lock up and are restricted from going forward; at the same time, they pull the tractor backwards. The tractor wants to keep going, and its second set of wheels have a tendency to drive the vehicle up under itself, raising the front wheels. This was nicknamed "popping a wheelie."

The problems for a rover, expected to meet plenty of bumps on Mars, were evident. If you could maintain the wheel load distribution without resorting to the use of an oscillation-producing spring suspension, you would increase the stability and terrain-negotiating performance of the vehicle. Through optimizing the geometry of a bogie system, Bickler produced the (now-legendary) rocker-bogie suspension design. No one is exactly sure who named this bit of engineering history: a six-wheeled chassis with a springless, articulated system that maintained even weight and traction on all the wheels — the simplest mechanism to satisfy the requirements without pantograph linkages

The Iterations of Rocky Rover

Don showed us photographs of the iterations of Rocky, as the robotics team experimented with electronics, batteries, materials, and loads. They even went to a farm equipment show to learn about struts. Rocky I, with 9.25-centimeter (3.66-inch) diameter wheels, could traverse steps and gaps over two wheel diameters, and climb over rocks about twice its size. The Rocky II design was abandoned before realized in hardware, but Rocky III was another improvement on the rocker-bogie design, with more mobility and lower surface pressures. Rocky III had 13-centimeter (5-inch) wheels, the same dimensions as the 1/8-scale table model of yore. (Bigger wheels work better in sand; smaller wheels sink.) Don showed us a photograph of a "dramatically overloaded" Rocky III being tested in the Mojave Desert, and here we observed the rover surrounded by robotics team members bearing the bemused expressions one sometimes sees on parents' faces as they watch a tottering but determined offspring engage the uneven terrain of the world. The vehicle, with all its apparatus, was so heavy that the metal wheels turned in the rubber tires — the experimenters had to use Crazy Glue to attach the tires to the wheels.

Sojourner Rover

The slimmed-down, sophisticated Rocky IV was a flight prototype version of Rocky III, with all-metal (rubber is not a desirable material on the cold surface of Mars) flexible wheels to get around better in sand and other soft materials. But the slotted wheels had a tendency to break and protrude, locking against the struts, so the next wheel design was solid metal. An iteration or two more, including Rocky VII, a close-coupled design intended to have one motor drive two wheels, and finally Rocky VIII — the elegant little rover that became Sojourner.

The naming of the rover, Don explained, was Donna Shirley's idea, and "it had to be female." (Donna Shirley was manager of the JPL Mars Exploration Program.) When informed that the rover would be named thusly, Don impishly proposed the name "Trixie." Donna affixed him with a look (and one can only imagine what that gaze conveyed), and proclaimed, "You've got nothing to do with it, Bickler!" A playful name was not to be; instead, the rover was eventually named in honor of the remarkable 19th-century American abolitionist and champion for women's rights, Sojourner Truth.

Q&A

During the question and answer portion of the storytelling, someone asked about optimum wheel size: how does one get there? It turns out that the wheel size is selected through exploring the solution space using a blend of human judgment and computer analyses. As Don pointed out, "a computer programmed to overlook flotation in soft sand would say that zero-diameter wheels are best." As to whether a Sojourner could be created in the "faster-better-cheaper" environment, Don's answer was "Absolutely!" It's engineering interest, not the prosaic limits of 40-hour weeks, that drives the process, and "we have a very big LEGO kit" for experimentation.

Another questioner asked about the biggest threat to the rover, and that, as might be surmised, is a situation where the rover somersaults. The rover allows for more than a wheel diameter of obstacle traversal, and can be symmetrical in forward/backward motion capability. A hazard-detection system is designed to prevent an overtipping condition by sensing pitch and roll; if pre-set limits are exceeded, the rover stops. Sojourner can actually climb a 45-degree slope (if the soil can be piled that steep), and can scale a 20-centimeter-high rock. If Sojourner were somehow flipped over, though, it could not right itself. Information on traversable obstacles (and the allowed traversability numbers are conservative) is stored on board, and if Sojourner encounters a non-traversable object (a rock too high), it is supposed to turn away and find another path. An interesting example of Sojourner meeting and evaluating an obstacle on Mars is captured in a brief movie at <http://mars.jpl.nasa.gov/MPF/ops/rvrmovie.html>. Open up the first item on the list, <rover_movie_sol24_S0050Q.gif>, and you'll see the rover bump a pyramid-shaped rock, turn, rotate 35 degrees, back up, and then blithely move forward as its right set of wheels clambers right over the rock. (Sojourner is capable of climbing over rocks twice that size.) The movie is a neat little example of the rover's climbing abilities, and provides a good view of how the suspension system and steering work.

Then there was the sand issue — could Sojourner get stuck? Don gleefully told the story. The team had tested the rover in sand created to "match Houston's recipe" for lunar soil, so they knew the rover was capable of traversing the fluffy stuff. A (nameless) challenger, citing M.G. Bekker's equations, maintained that the JPL rover was such a poor design that it could not handle a downhill slope. The challenger was politely invited to come to JPL, where a hole was dug in the simulant for the rover. Sojourner, of course, promptly climbed right out.

At the end of the too-short hour, Barbara Amago thanked Don and presented him with a small crystal globe, the customary gift that represents the jewels of insight brought to us by the JPL storytellers.

Eyeing it appreciatively, The Bogie Man pronounced it "one heck of a marble."

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Web Sites of Interest

http://robotics.jpl.nasa.gov/tasks/scirover/genealogy/homepage.html — Timeline of JPL Mars rover development.

http://mars.jpl.nasa.gov/MPF/rovercom/pixt.html — Mars Microrover photo gallery. Here are many pictures of various rovers as well as photos from the Pathfinder mission. Includes a composite image comparing the size of Sojourner with the Apollo Lunar Roving Vehicle.

http://www.delphion.com — The 1989 rocker-bogie patent. Type in "Bickler" and a list of patents comes up, including no. 4,840,394 for the 1989 articulated suspension system.

http://mpfwww.jpl.nasa.gov/rovercom/rovintro.html — Information on Sojourner (Mars Microrover).

http://www.bchip.com/mars/rover/descrip.html — Detailed description of Sojourner rover.

http://mars.jpl.nasa.gov/MPF/ops/rvrmovie.html — "Movies" of Sojourner on Mars.

http://www.bchip.com/mars/rover/name.html — How Sojourner rover got its name.

http://www.sojournertruth.org/ — The Sojourner Truth Institute Web site.

http://www.digitalsojourn.org/speech.html — Sojourner Truth's famous 1851 speech.

http://www.osa.com.au/~cjh/lego/ — An Australian hobbyist's palm-sized Sojourner model built of LEGO blocks, with a miniature rocker-bogie system.

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