SPACE EXPLORERS!

After mapping the asteroid Eros from a close orbit, the NEAR probe was commanded to set down on its surface. An ingenious plan to take off again and transmit close-up images was frustrated when the simple-minded robot exhausted its rocket fuel trying fruitlessly to adjust the orientation of the asteroid. Photo provided by Michael Buckley, Johns Hopkins University Applied Physics Laboratory.

The evolution of robotic arms and mobility in the space age

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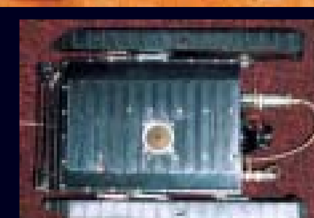
Our admiration for the space robots already loose in the Solar system, and the follow-on hardware now in preparation, can be enhanced even more when we consider how far this technology has progressed since the dawn of the Space Age. Back then, engineers tried to build devices that had simple arms and hands, and had simple mobility systems, along with their sensors and autopilots—and that's what made them 'space proto-robots', the ancestors of today's machines.

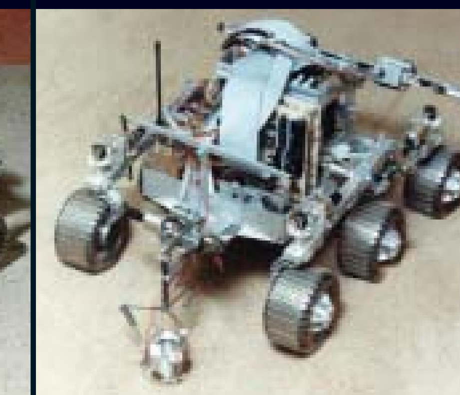
There's a practical purpose in knowing how these earliest space robots were built. Sometime in the future, as hands and senses, both human and mechanical, disperse out farther in the solar system, emergencies will occur. Some astro-McGuyver will need to lash up a simple robot from bench parts and leftovers from broken machines. And when that happens, the simplest and most primitive design—grabbed from the history books or half-forgotten memories—may be the best choice.

The evolutionary benchmark that made some of the earliest space probes more than just probes, but proto-robots, were two functions characteristic of the modern breed—the ability to manipulate and the ability to move. And some types of space hardware from those early years began to attempt exactly such functions, on the moon and on Mars, with highly varying degrees of success.

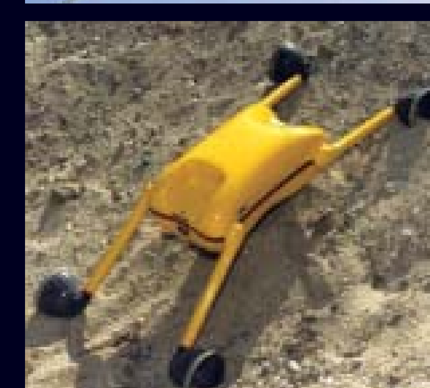


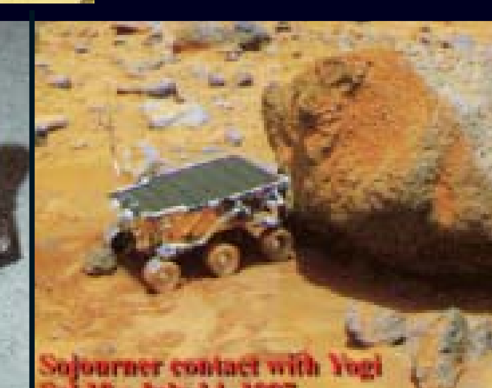
Never-before-published images of a lunch-box-size Russian Mars crawler that would have been the first rover on the Red Planet in 1971. Unfortunately, its mother ship crashed, and the project was covered up for decades. Photos courtesy of Babakin Institute, Moscow, and David Woods.

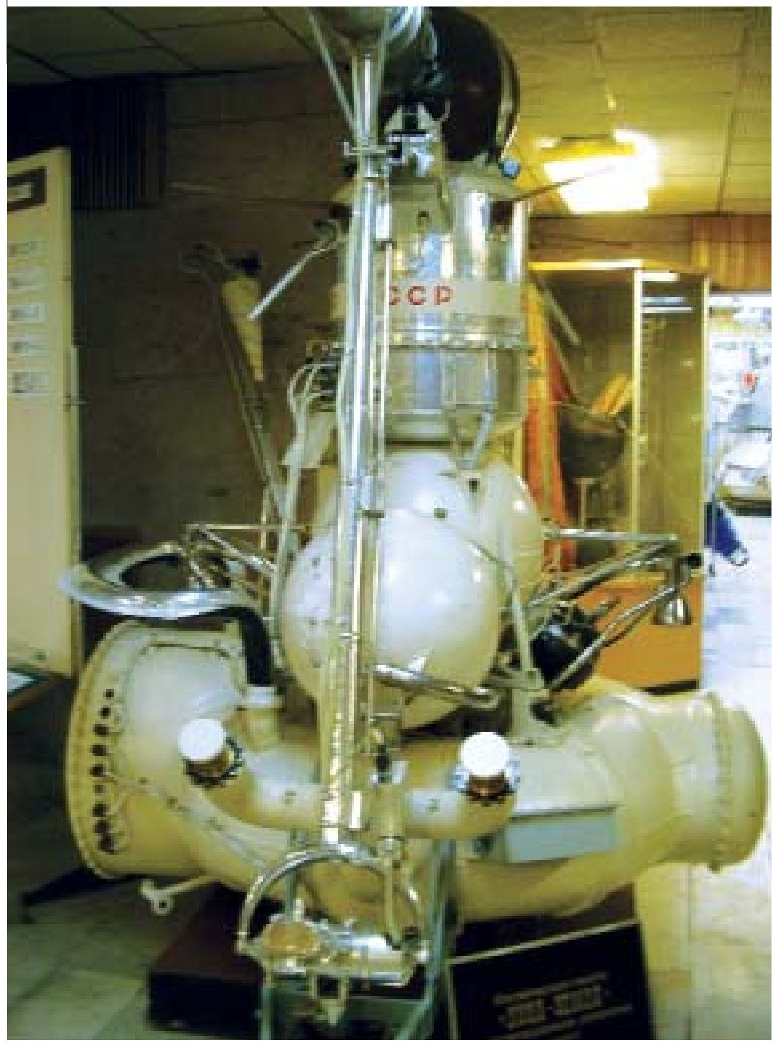
PHOTOS COURTESY OF THE MOSCOW SPACE MUSEUM, NASA AND JPL



Potpourri of early NASA Mars Rover designs, leading to the Sojourner mini-rover deployed by the Pathfinder lander in 1997. Left—the Sojourner (and human friend) next to its direct descendant, the much larger (and long-lived) Spirit and Opportunity class of rover.







Moscow Space Museum displays the return stage and landing capsule of a Russian robot that brought back small amounts of moon dirt in 1970. The simple robot arm that placed the samples into the return capsule is in front. Photo courtesy of Digby Tarvin.

TRENCH DIGGERS

The first arm on a space robot was installed on lunar probes named Surveyor. Seven were launched in 1966-1968, and five made safe landings. The arm had a scisssors-mechanism extension system and a simple scoop with a motorized wrist at the end. Its shoulder allowed the arm to sweep through an arc of 112 degrees. The arm moved between two of the lander's three legs and could reach the ground 60 to 90 centimeters from the shoulder. The end-mounted scoop could be lifted a meter above the surface, and with lots of digging, could reach a depth of 50 centimeters below the surface.

Monitored through several TV cameras, the arms were used to dig trenches and test the soil for cohesion. The scoop was pressed down hard to measure soil compaction. Samples of the soil were placed into test instruments, to measure chemical, magnetic, and mechanical properties.

The Surveyor program (and in particular its key mechanism, the robot arm) verified the design of the Apollo Lunar Module for touching down on the Moon and not being adversely affected by unusual properties of the soil. Another roving lunar robot named Prospector was designed but then cancelled as the Apollo astronaut schedule picked up speed. However, the success of the Surveyor's arm led directly to the robot arms installed on the Viking landers that flew to Mars ten years later.

As originally planned, later Surveyor probes would have carried more scientific instruments and even small wheeled rovers. But by the time it became necessary to seriously fund and build such vehicles, the Apollo program was gathering steam—and devouring funds. America's plans for robot wheeled rovers were put on hold for thirty years.

But even without wheels, Surveyor also, through inspired improvisation, pioneered the second aspect of a true space robot: mobility. The Surveyor-6 robot, at the end of its research program, briefly fired its small stabilization rockets—used during the touchdown—and hopped back off the surface. It thumped down about 2.5 meters from its original location and was able to take detailed photographs of its original footpad holes and of the scouring effect of its rocket engine on the soil—a critical concern for possible debris bounce-back damage to the Apollo landers that were soon to follow.

This Surveyor moon robot arm (scissors design) was photographed by Apollo astronauts, who visited it in 1969.

LUNOKHOD PIONEERS BOT MOBILITY

Useful mobility on the Moon was pioneered by two Russian space robots named 'Lunokhod'—where 'luna' was the moon, and '-khod' designated a 'mover'.

On November 17, 1970—a year and a half after the Apollo-11 astronauts had landed on the Moon and walked across its surface—a Soviet probe named Luna-17 set down softly. Within hours, it unfolded its ramps, one set forward and one set aft (in case of surface obstructions), and the motorized Lunokhod-1 trundled out onto the surface.

Looking like a fat wheeled turtle 220 centimeters long, the rover had eight metal-mesh 50 cm diameter wheels supporting its total weight of half of a ton (on Earth—only one sixth of that on the Moon). A motorized lid could open in daytime, exposing solar cells, and close at night to conserve heat from small radioactive generators. Television cameras were mounted in front and along the sides.

Two teams of drivers operated the rover from a control room in Moscow. They changed direction like military tanks do, altering speed between the two sets of wheels. The rover drove south at up to 2 km/hour, examining soil and craters, for about a month, reaching a distance of about 1300 meters from the landing platform. They then demonstrated the accuracy of their navigation system (which included a free-turning spiked ninth wheel trailing behind the main body to measure the actual distance traveled) by heading northeast and then jogging northwest to return to their landing point. Over the following months they headed into unknown territory, eventually covering 10.5 kilometers before the rover's batteries faded and it was parked forever.

Seven-wheeled Soviet 'Lunokhod' moon rover, a backup unit to two rovers that successfully reached the moon in the early 1970s. Photo courtesy of Digby Tarvin.

Lunokhod traveled a lot faster and farther than the Mars' rovers Spirit and Opportunity because of the man-in-the-loop control, even with the 3 second round-trip time for radio signals. Aside from its remarkable engineering, it stands as a reminder of how far space robots still have to go in order to match traverse speeds that human-controlled rovers can achieve.

A second Lunokhod was successfully delivered to the surface by Luna-21 in 1973, and several others crashed on landing. But the remarkably successful project and its cute wheeled robots soon ended, overtaken by the even faster rovers on later Apollo missions, where on-the-scene astronaut drivers achieved speeds of 8 km/hour and covered distances of as much as 35 kilometers in only three days of operation.

SOIL SAMPLING

Meanwhile, another type of Soviet moon robot had trumped that surface-to-surface mobility by sending a canister of collected moon dust all the way back to Earth. The Luna-16 probe landed in the Moon's Sea of Fertility in September 1970, and an arm-mounted drill grabbed 100 grams of surface soil, swung up to the nose of the probe, and inserted it into a capsule with a small rocket engine attached. The plan had been to drill 30 centimeters into the soil but the drill had quickly hit a rock and stopped with only a fraction of the hoped-for samples collected.

The Soviet engineers had designed a very simple guidance routine for the return trip to Earth: blast off straight up until the rocket burned out. To make this work, and to actually hit the target planet (even with small steering rockets used to correct the homeward course), they employed an elegantly simple solution. They chose the landing site on the trailing equatorial region of the Moon so that a straight-up launch would result in the capsule 'hanging' in space as the Moon moved away from it—and Earth's gravity just pulled it straight 'down'. This clever principle—design the mission around the limitations of the robot's "smarts"—kept the project cheap enough and practical enough for success.

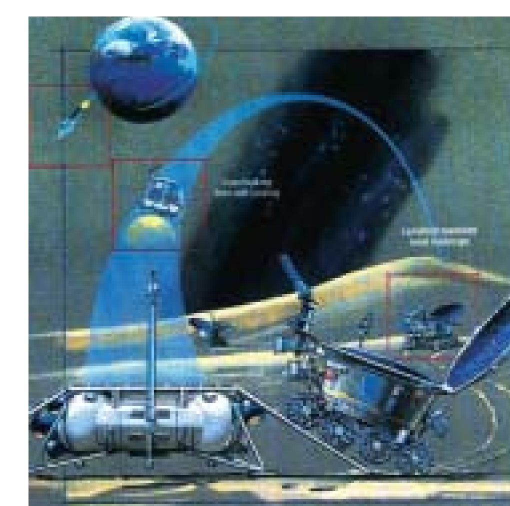
But not all the time. By an ironic twist of lunar cartography, the smoothest region in that limited section of the Moon was named Sea of Crises. Three landing attempts (including one launched just prior to the Apollo-11 astronaut mission in July, 1969) all failed in this region. Luna-16 in late 1970, and Luna-24 a few years later, did succeed.

Luna-24's robotic soil retrieval system was particularly ingenious. Instead of a sample soil grabber, it carried a drill mechanism that was supposed to penetrate as much as 2.5 meters below the surface. The retrieved core of dust and small pebbles was collected in a plastic sleeve, which was then pulled into the return capsule and wound up in spiral fashion inside a prepared hollow. The actual sample, with its well-preserved stratigraphy, was about 1.6 meters long—apparently the drill had been stopped by a rock, but not until achieving most of its science objectives.

As with the very promising Lunokhod moon buggy, the Soviet 'moon sampler' program was quietly cancelled soon after the American Apollo lunar landings ended. Follow-on missions of much greater scientific value, including operations on the far side of the Moon using communications relay satellites, did not interest the Kremlin. Robots, unlike cosmonauts and astronauts, apparently held little propaganda value.

FIRST ROBOT MISSIONS TO MARS

But sexier, farther worlds did—and Mars was first on that list. Soviet probes had begun in 1960, years before the Americans, but there had only been an unbroken string of failures, most kept secret.



Bigger rockets allowed the launching of heavier probes beginning in 1969, and on one of those missions, Russian engineers built the first Mars robot intended to be mobile. It was installed inside a 'mother ship' but that vehicle failed on route to Mars. So the robot never had a chance to be deployed—and the project was kept secret for decades. Only in recent years have the outlines of that project, and the first grainy images of the hardware, become available to the outside world.

The lunch-box sized mini-rover (Earth weight: 4.5 kilograms) would have scrunched its way forward by use of side-mounted skis that pushed the ground backwards as struts at the front and back rotated. The unit trailed an electrical umbilical to the main lander, which was solar powered, and it was supposed to get about 15 meters out and take pictures of its new surroundings, including the main capsule that had deployed it. It could reverse its course, and the left and right skis could be programmed to move separately to steer, as needed.

This locomotion mechanism was the ultimate in simplicity, and it never had a chance to be tried out (after a string of failures, the Soviets cancelled their program when they were upstaged by NASA's much more sophisticated Viking landers in 1976). It would have taught scientists a lot about the Martian soil, but even more importantly, it would have—and still can—teach future space robot designers about the utility of crude but functional 'bare-bones' design.

Viking, for all its technological capabilities (and massive cost), was never designed to be mobile. The purpose of the two lander probes (and the two orbiting probes that deployed them) was to ask Mars if there was life on the planet. In the end, the response from Mars was, "Please rephrase the question."

Russians planned a hopper mini-robot for the low-gravity Martian moon Phobos, but both mother ships broke down before the hoppers could be deployed. Not visible underneath is a spring-loaded pogo stick that would have launched the hopper upward to land tens of meters away. The four wires were to have oriented the probe on the surface for proper pogo stick actuation.

VIKING ARMS

To perform the biochemical tests on Martian dirt, the two Viking landers used a robot arm similar in capabilities to the arm installed on the surveyor moon landers a decade earlier. But the arm was built on an entirely different mechanical principle.

Instead of using the folding-scissors design, the 3 meter long, 6.2 cm diameter Viking boom was an unfurlable steel tube with two ridges welded down opposite sides. In the undeployed state the cylinder shape was flattened and rolled up, but as it was extruded from the storage mechanism (using sprocket drives engaging holes in the side-mounted ribbons) it sprang into its round cross section.

The motorized shoulder joint (which also could rotate the whole boom left/right about 108 degrees) allowed the boom to place the sampler head over a large area near the lander. There it could dig, insert instruments into the soil, grab samples, sieve the dirt, and deliver samples to a variety of instruments. It could also hold a magnifying mirror up to various spacecraft components not directly visible to the lander's cameras. The arms on both Viking landers operated magnificently for months, until contact was lost.

Detail of the Viking robot arm. It was compressed and rolled up inside the deployment box, and then assumed its cylinder shape as it was extended.

ATTAINING ROBOTIC MOBILITY

Attaining mobility on Mars became the new challenge, and the US and Russia pursued variations of this theme along two different paths. NASA built the wheeled Sojourner shoe-box size test rover that operated successfully on Mars in mid-1996 and cleared the way for the much larger and more capable Spirit and Opportunity rovers. The Russians pursued a bold plan for exploring the Martian moon Phobos that involved deploying two small 'hopper' probes that would reach the surface, right themselves, and then launch upward to come down tens of meters away—but two separate Russian probes both broke down before reaching Phobos, and the hoppers remained attached to their derelict mother ships, floating in space near Mars.

A fitting and illuminating incident marks a proper conclusion to this survey of 'historical space robots'. Only a few years ago, another space robot attempted surface mobility on the asteroid Eros, another improvised experiment at the end of the highly successful NEAR (Near-Earth Asteroid Rendezvous) mission. Once the long survey from orbit was completed, mission managers added the unplanned step of laying the probe safely onto the surface. Taking sharper and sharper pictures all the way down, the probe safely landed on the low-gravity world.

As it tilted over, its high-gain antenna pointed away from Earth, and so the transmission of the best images in the final hundred meters failed. Although exultant over the safe landing, the controllers quickly developed a bold plan to fire up the probe's engines and take off again so that its orientation engines would properly align the antenna and replay the stored images. They threw the command sequence together and sent it up to the probe, at that point so far from Earth that signals took 20 minutes to reach it.

It didn't work. The probe never moved again. Operators quickly realized their mistake. Since the original touchdown had been designed to be the final point of the mission, nobody had thought to upload a command to turn off the craft's stabilization jets after touchdown. So once the robot's autopilot detected it was out of proper orientation (it was being leaned on by an asteroid!), it dutifully fired its steering jets in an attempt to turn itself (and the asteroid) back towards Earth. The fuel was exhausted long before the asteroid even began to budge—and just before the command to use leftover fuel to lift itself briefly off the asteroid for the photo transmission.

Space robots are like that: without common sense, out-of-the-ordinary situations can lead them to follow normal procedures and do stupid things. That lesson, and the dozens of other clever mechanical innovations that these probes delivered, constitute their enduring legacy. ◎