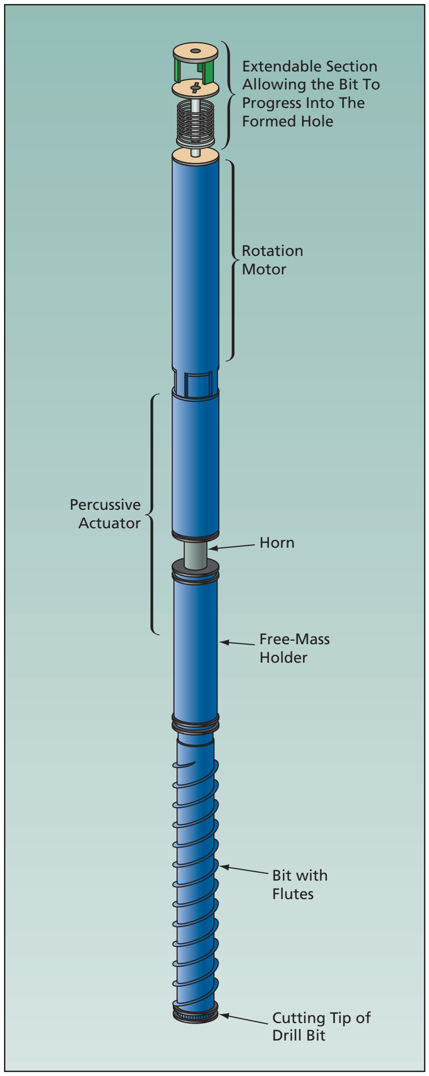
only by use of much longer, heavier, conventional drilling-and-sampling apparatuses.

To recapitulate from the prior articles about USDCs: A USDC can be characterized as a lightweight, low-power jackhammer in which a piezoelectrically driven actuator generates ultrasonic vibrations and is coupled to a tool bit through a free mass. The bouncing of the free mass between the actuator horn and the drill bit converts the actuator ultrasonic vibrations into sonic hammering of the drill bit. The combination of ultrasonic and sonic vibrations gives rise to a hammering action (and a resulting chiseling action at the tip of the tool bit) that is more effective for drilling than is the micro-hammering action of ultrasonic vibrations alone. The hammering and chiseling actions are so effective that the size of the axial force needed to make the tool bit advance into soil, rock, or another material of interest is much smaller than in ordinary rotary drilling, ordinary hammering, or ordinary steady pushing.

The predecessor of the rotary percussive auto-gopher is an apparatus, now denoted an ultrasonic/sonic gopher and previously denoted an ultrasonic gopher, described in "Ultrasonic/Sonic Mechanism for Drilling and Coring" (NPO-30291), *NASA Tech Briefs* Vol. 27, No. 9 (September 2003), page 65. The ultrasonic/sonic gopher is intended for use mainly in acquiring cores. The name of the apparatus reflects the fact that, like a gopher, it periodically stops advancing at the end of the hole to bring excavated material (in this case, a core sample) to the surface, then re-enters the hole to resume the advance of the end of the hole. By use of a cable suspended from a reel on the surface, the gopher is lifted from the hole to remove a core sample, then lowered into the hole to resume the advance and acquire the next core sample.



Anchoring and Rotary Mechanisms and a fluted drill bit would be added to an ultrasonic/sonic gopher.

The rotary percussive auto-gopher would include an ultrasonic/sonic gopher, to which would be added an anchoring and a rotary mechanism and a fluted drill bit (see figure). If, as intended, the ultrasonic/sonic gopher were rotated, then as in the case of an ordinary twist drill bit, the flutes would remove cuttings from the end of the hole, thereby making it possible to drill much faster than would be possible by ultrasonic/sonic hammering and chiseling action alone. The anchoring mechanism would brace itself against the wall of the drilled hole to enable the rotary mechanism to apply a small torque and a small axial preload to rotate the ultrasonic/sonic gopher drill bit and push the drill bit against the end of the hole. The anchoring and rotary mechanisms would be parts of an assembly that would follow the ultrasonic/sonic gopher down the hole.

This work was done by Yoseph Bar-Cohen, Mircea Badescu, and Stewart Sherrit of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). NPO-45949

More About Reconfigurable Exploratory Robotic Vehicles

Essential to reconfigurability is modularity of hardware and software.

NASA's Jet Propulsion Laboratory, Pasadena, California

Modular exploratory robotic vehicles that will be able to reconfigure themselves in the field are undergoing development. These vehicles at the initial concept stage were described in "Reconfigurable Exploratory Robotic Vehicles" (NPO-20944), *NASA Tech Briefs*, Vol. 25, No. 7 (July 2001), page 56. Proposed for use in exploration of the surfaces of Mars and other remote planets, these vehicles and others of similar design could also be useful for exploring hostile terrain on Earth.

To recapitulate from the cited prior article: the modular vehicles are denoted generally by the term Axel*n*, where *n* is an even number equal to the number of main wheels. The simplest vehicle of this type is Axel2 — a two-main-wheel module that superficially resembles the rear axle plus rear wheels of an automobile (see Figure 1). In addition to the two main wheels, an Axel2 includes a passive caster wheel attached to the axle by an actuated caster link. The motion of the caster link can be used to control the rotation of the axle in order to tilt, to the desired angle, any sensors mounted on the axle. In addition to the sensors, the axle of an Axel2 houses computer modules and three motors and associated mechanisms for driving the main wheels and the caster link. An Axel2 is powered by rechargeable batteries located inside the wheel hubs.

One constructs an Axel*n* ($n > 2$) as an assembly of multiple Axel2s plus one or more instrument module(s) connected to each other at module interfaces (see Figure 2). The module interfaces contain standardized electrical and mechanical connections, including spring-loaded universal joints that afford some compliance to enable the modules to rotate, relative to each other, to adapt to terrain. Data are communicated between modules via fast serial links in the module interfaces.

An Axel*n* amounts to a train carrying $n/2 - 1$ instrument modules. The instrument modules contain additional computational units that, in addition to processing of instrument readings, contribute to coordination of motion. In other words, the "intelligence" of an Axel*n*, and thus the sophistication of the maneuvers that it can perform, increase with *n*. The symmetrical design of the modules enables them to operate in any stable orientation, including upsidedown; this feature contributes to robustness of operation in rough terrain. A fully developed Axel*n* would be able to diagnose itself to detect nonfunctional modules.

Going beyond the description in the cited prior article, the following additional major items of the hardware can now be reported.

Also contained within the axle of an Axel2 is a stereoscopic pair of electronic cameras to be used for navigation across terrain, for scientific observations, and for guidance in docking maneuvers.

Each module interface is an electromechanical module located at the midlength of the axle of an Axel2. The module interface carries female parts of mating mechanisms, while instrument modules carry the male parts. The mating mechanisms include conical mating surfaces that correct for small initial misalignments to facilitate autonomous coupling of an Axel2 with an instrument module.

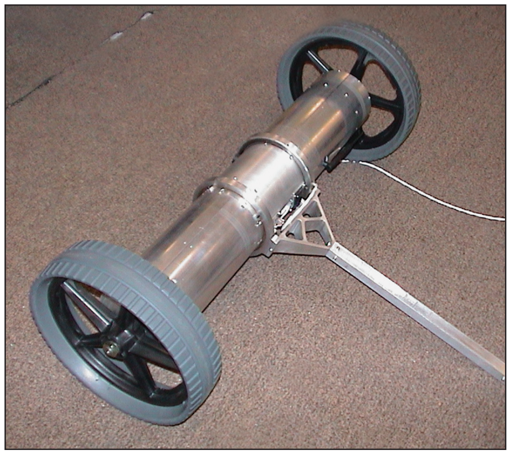


Figure 1. This **Two-Wheeled Vehicle** is a prototype of an Axel2.

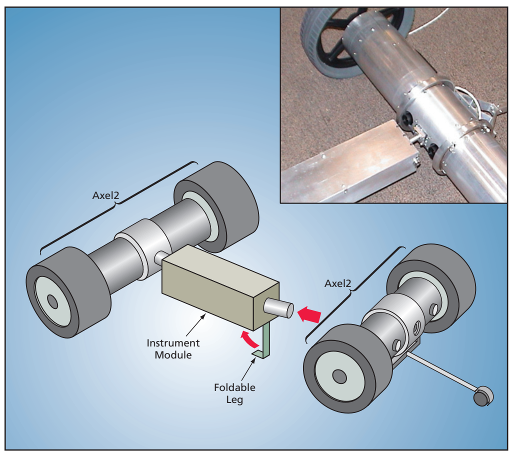


Figure 2. The **Prototype Axel2 and a Prototype Instrument Module** are depicted here during a docking maneuver that ends in coupling at the module interface.

Information on the Axel*n* software has become available since the prior article was published. To enable self-diagnosis and automatic reconfiguration of modular hardware, the architecture of the Axel*n* software provides for autonomous adaptation of the software to the hardware reconfiguration. More specifically, an Axel*n* uses software that can determine when physical reconfiguration is necessary (e.g., in response to task requirements or hardware failures), controls the hardware reconfiguration, and reconfigures itself to conform to the changed hardware configuration.

The capability for autonomous reconfiguration of the hardware depends heavily on the supporting software. One of the goals of the development of the Axel*n* system is to simplify and generalize through modularity. The reconfigurable software architecture mirrors the modularity of the hardware by providing that, as hardware modules are connected or disconnected, associated software modules are also put into or taken out of operation.

This work was done by Ayanna Howard, Issa Nesnas, Barry Werger, Daniel Helmick of Caltech; Murray Clark and Raymond Christian of Arkansas Tech; and Raymond Cipra of Purdue University for NASA's Jet Propulsion Laboratory. For more information, contact iaoffice@jpl.nasa.gov.
NPO-30890

Thermostatic Valves Containing Silicone-Oil Actuators

NASA's Jet Propulsion Laboratory, Pasadena, California

Flow-splitting and flow-mixing thermally actuated spool valves have been developed for controlling flows of a heat-transfer fluid in a temperature-regulation system aboard the Mars Science Laboratory (MSL) rover. Valves like these could also be useful in terrestrial temperature-regulation systems, including automobile air-conditioning systems and general refrigeration systems. These valves are required to provide smoother actuation over a wider temperature range than the flow-splitting, thermally actuated spool valves used in the Mars Explorer Rover (MER). Also, whereas the MER valves are unstable (tending to oscillate) in certain transition temperature ranges, these valves are required not to oscillate.

The MER valves are actuated by thermal expansion of a wax against spring-loaded piston rods (as in common automotive thermostats). The MSL valves contain similar actuators that utilize thermal expansion of a silicone oil, because silicone-oil actuators were found to afford greater and more nearly linear displacements, needed for smoother actuation, over the required wider temperature range. The MSL valves also feature improved spool designs that reflect greater understanding of fluid dynamics, consideration of pressure drops in valves, and a requirement for balancing of pressures in different flow branches.

This work was done by Pradeep Bhandari, Gajanana C. Birur, David P. Bame, Paul B. Karlmann, and Mauro Prina of Caltech and William Young and Richard Fisher of Pacific Design Technology for NASA's Jet Propulsion Laboratory.

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to:

Innovative Technology Assets Management
JPL
Mail Stop 202-233
4800 Oak Grove Drive
Pasadena, CA 91109-8099
E-mail: iaoffice@jpl.nasa.gov

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