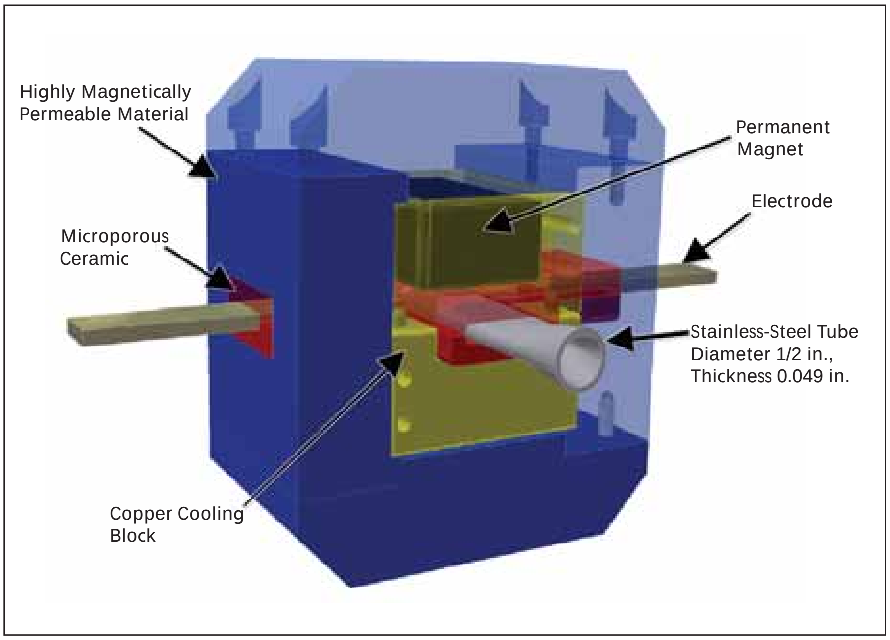

This **Direct-Current Electromagnetic Pump** is designed to develop a pressure of 5 psi (34 kPa) and a mass flow rate of 56 g/s when driven by an input current between 50 and 100 ADC (corresponding to an input potential of about 1 VDC). The pumped fluid would be a sodium-potassium eutectic at a temperature of about 650 °C.

magnetic field perpendicular to both the longitudinal axis and the electric current is superimposed on the flow-channel region containing the electric current. The interaction between the electric current and the magnetic field produces the pumping force along the longitudinal axis. The advantages of the proposed pump over other such pumps would accrue from design features that address overlapping thermal and magnetic issues.

Under the anticipated operating conditions, the molten alkali metal — a eutectic mixture of sodium and potassium — would be heated to a temperature of about 650 °C. To maximize the effectiveness of the pump while minimizing the electric current (and thus the power) needed for pumping at a given rate, it is necessary to maximize the magnetic field across the flow channel. In order to do this, it would be desirable to use rare-earth (specifically, neodymium or samarium-cobalt) permanent magnets to apply the magnetic field and to place the magnets as close as possible to the flow channel. Because such magnets become demagnetized at temperatures around 130 or 350 °C, respectively, it becomes necessary to protect them against conduction and radiation of heat from the flow channel. In some other pumps of this type, the thermal-protection problem is solved by placing the magnets farther from the channel and then increasing the electric current needed to obtain the required pumping capacity. In still other pumps of this type, massive amounts of convection cooling are used to prevent overheating of the magnets.

In the proposed pump, the liquid metal flow channel would be defined by a round stainless-steel tube that would be flattened to a nearly rectangular cross section in the region where the magnets were to be placed (see figure). Two permanent magnets would be placed on opposing sides of the channel, separated from the flat tube faces by thermal-insulation material consisting of a microporous ceramic having extremely low thermal conductivity. To remove the small amount of heat conducted through the ceramic, copper blocks housing the magnets are connected to a water-circulation cooling system. These blocks would be in direct thermal contact with each magnet, providing an isothermal heat sink to maintain the temperature below a required level. To maximize the magnetic flux density in the channel, the part of the magnetic circuit outside the channel would be completed with ferromagnetic material having a magnetic permeability and a magnetic-saturation threshold greater than those of simple iron.

Thick electrodes would conduct the applied electric current to the tube walls, and the current would be conducted through the tube walls to the liquid metal in the channel. A portion of the current would be conducted around the channel through the tube walls; this portion would not be available for generating pumping force. Hence, unavoidably, some power would be lost in heating of the tube walls.

This work was done by Thomas Godfroy and Kurt Polzin of Marshall Space Flight Center. For further information, contact Sammy Nabors, MSFC Commercialization Assistance Lead, at sammy.a.nabors@nasa.gov. Refer to MFS-32597-1.

Progress in Development of the Axel Rovers

Robots like these could be used to search for victims of disasters.

NASA's Jet Propulsion Laboratory, Pasadena, California

Progress has been made in the development of a family of robotic land vehicles having modular and minimalist design features chosen to impart a combination of robustness, reliability, and versatility. These vehicles at earlier stages of development were described in two previous *NASA Tech Briefs* articles: "Reconfigurable Exploratory Robotic Vehicles" (NPO-20944), Vol. 25, No. 7 (July 2001), page 56; and "More About Reconfigurable Exploratory Robotic Vehicles" (NPO-30890), Vol. 33, No. 8 (August 2009), page 40. Conceived for use in exploration of the surfaces of Mars and other remote planets, these vehicles could also be adapted to terrestrial applications, including exploration of volcanic craters or other hostile terrain, military reconnaissance, inspection of hazardous sites, and searching for victims of earthquakes, landslides, avalanches, or mining accidents. In addition, simpli-

Figure 1. A **Prototype Axel Rover** can operate in a free or tethered configuration. Testing of this version is complicated by a need to properly wrap the power cable around the axle housing. It has been proposed to eliminate the power cable and install rechargeable batteries in a future version.

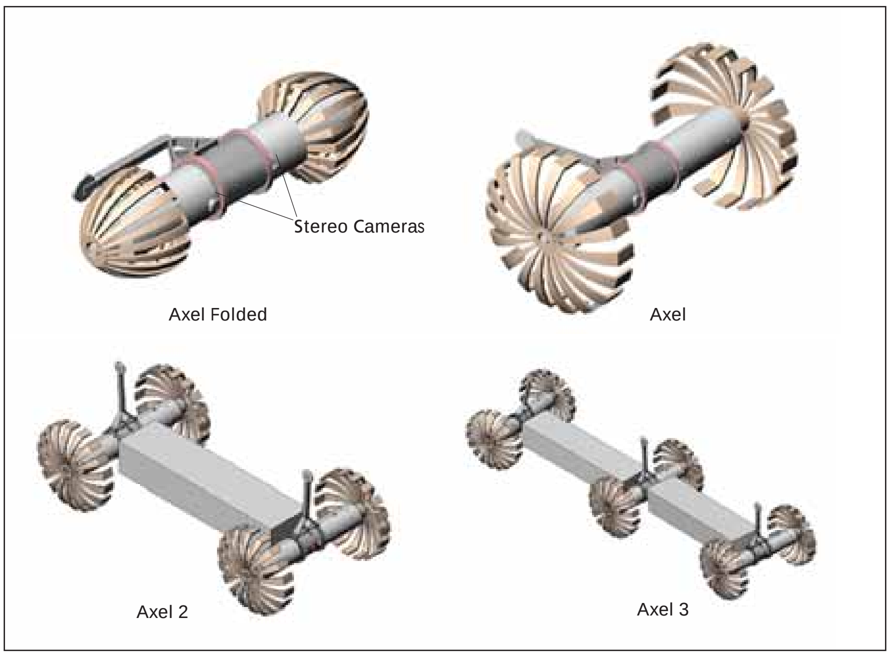

Figure 2. **Extended Axel Configurations** show design versatility.

fied versions of these vehicles might be marketable as toys.

The most basic module in this family of reconfigurable robots is the Axel rover, which has a cylindrical body with two main wheels and a trailing link. Inside its body are three motors and associated mechanisms for driving the two wheels and for rotating the link 360º around its symmetrical body. The actuated link serves several purposes:

- It is used as a lever arm to react to the wheels thrust to move Axel in multiple directions.
- It is used to rotate the Axel housing in order to tilt, to the desired angle, any sensors and instruments mounted on or in the Axel housing.
- It provides an alternative mobility mode, which is primarily used in its tethered configuration. Turning the link into the ground in lieu of driving the wheels causes the Axel housing and wheels to roll as a unit and thereby leads to a tumbling motion along the ground. With a tether mounted around Axel's cylindrical body, the link serves as a winch mechanism to reel and unreel the tether raising and lowering Axel over steep and vertical surfaces (Figure 1).

Sensors, computation, and communication modules are also housed inside Axel's body. A pair of stereo vision cameras provides three-dimensional view for autonomous navigation and avoiding obstacles. Inertial sensors determine the tilt of the robot and are used for estimating its motion. In a fully developed version, power would be supplied by rechargeable batteries aboard Axel; at the time of reporting the information for this article, power was supplied from an external source via a cable.

In and of itself, the Axel rover is fully capable of traversing and sampling terrains on planetary surfaces. By use of only the two main wheel actuators and the caster link actuator, Axel can be made to follow an arbitrary path, turn in place, and operate upside-down or right-side-up. If operated in a tethered configuration, as shown in Figure 1, it can be made to move down and up a steep crater wall, descend from an overhang to a cave, and ascend from the cave back to the overhang, all by use of the same three actuators. Such tethered operation could be useful in searching for accident victims or missing persons in mines, caves, and rubble piles. Running the tether through the caster link enhances the stability of Axel and provides a restoring force that keeps the link off the ground for the most part during operation on a steep slope.

In its extended configuration, two Axel modules can dock to either side of a payload module to form the four wheeled Axel2 rover (Figure 2). Additional payload and Axel modules can dock to either side of the Axel2 to form the Axel3 rover, extending its payload capacity and its mobility capabilities.

This work was done by Issa A. Nesnas, Daniel M. Helmick, Richard A. Volpe of JPL, Pablo Abad-Manterola, and Jeffrey A. Edlund of Caltech; Raymond Cipra and Damon Sisk of Purdue University; and Raymond H. Christian and Murray R. Clark of Arkansas Tech University for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). NPO-45553