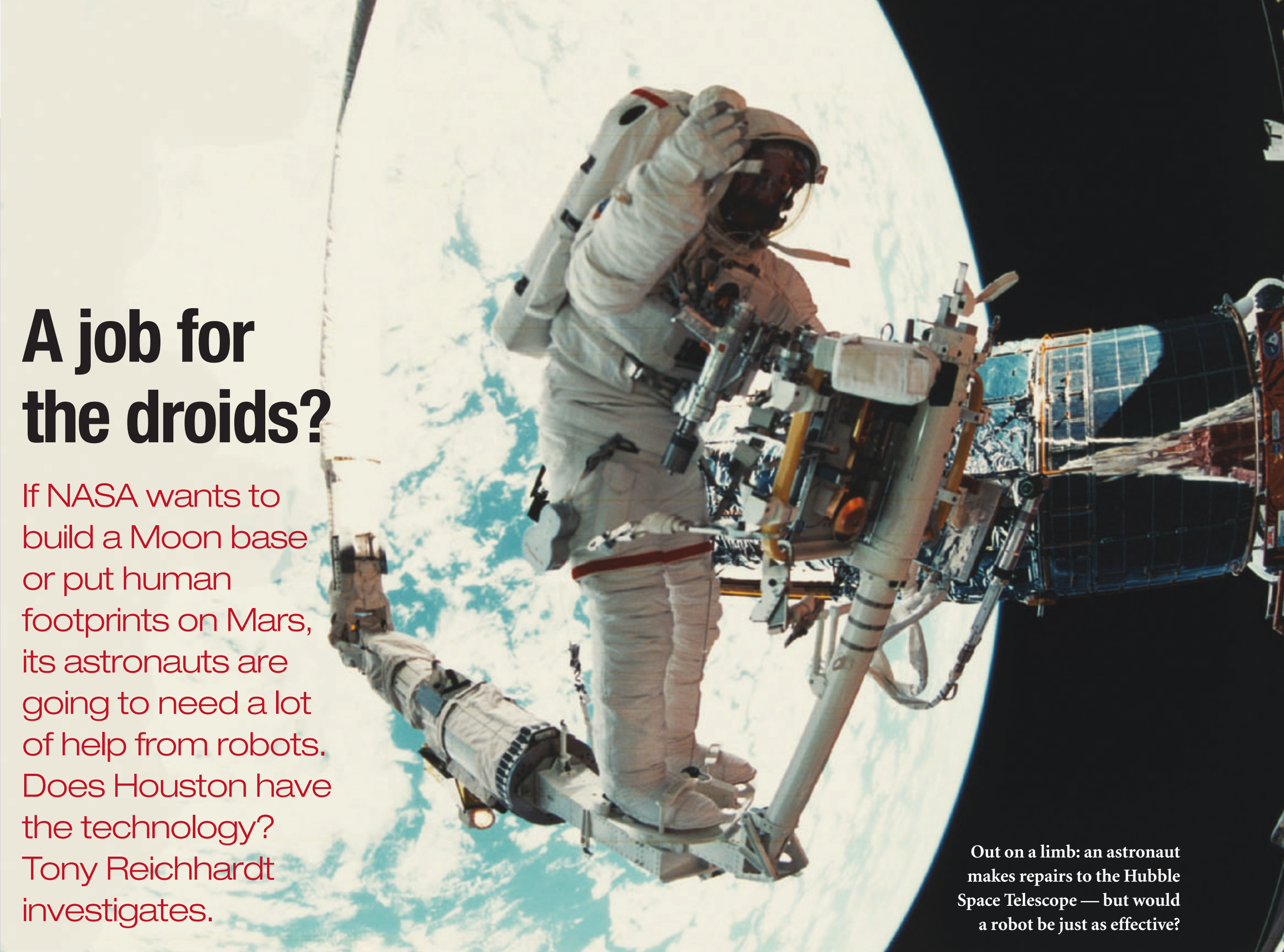

A job for the droids?

If NASA wants to build a Moon base or put human footprints on Mars, its astronauts are going to need a lot of help from robots. Does Houston have the technology? Tony Reichhardt investigates.

Out on a limb: an astronaut makes repairs to the Hubble Space Telescope — but would a robot be just as effective?

R. RESSMEYER/NASA/CORBIS

In January 1960, Swiss physicist Jacques Piccard and US Navy Lieutenant Donald Walsh made humanity's first voyage to the deepest spot in the ocean. Aboard the vehicle *Trieste*, they spent 20 minutes on the muddy bottom of the Mariana Trench, 11 kilometres beneath the surface. During their stay, the *Trieste* protected them from a crushing pressure 1,000 times greater than that found at the sea's surface. Before going home, they left behind an American flag in a weighted plastic container to commemorate their historic trip.

In 44 years, no one has tried to go back. Instead, uncrewed vessels have been pressed into service. Although manned submersibles still have passionate defenders, most of the action in deep-sea exploration has switched to robotics. A similar trend can be seen elsewhere: from offshore oil drilling to military reconnaissance, robots are taking on more of the dull, dirty or dangerous jobs.

Will the same shift happen in space, where the cost and risk of human exploration are far greater? At first glance, the glamorous nature of human spaceflight might indicate otherwise. President Bush's vision for NASA calls for sending astronauts beyond Earth's orbit for the first time since 1972 — despite widespread scepticism, particularly among scientists, that launching astronauts is the best way to explore space. But senior NASA officials stress that, in contrast with the Apollo programme, this time robots will share top billing. "When we do go to Mars, we're going to do most of the work with the robots," Gary Martin, NASA's 'space architect' responsible for long-range planning, recently told the Space Studies Board of the US National Academy of Sciences.

Automatic response

Peter Will, a roboticist at the University of Southern California in Los Angeles, likes what he's hearing. A veteran of the field — he built one of IBM's first industrial robots in the early 1980s — Will thinks that constructing habitats and associated infrastructure for a long-term human presence on the Moon cannot be done by people alone. "The whole thing has got to be done robotically," Will says. "Maybe all the glamour will go to humans," he concedes, but robots are likely to have to pave the way.

So, does NASA have the right experience and skills in robotics to match its ambitions? In the 1990s, the agency invested at a moderate but steady level in general robotics research, with the budget peaking at $24 million a year in 1997. The money went to projects such as Dante II, an eight-legged walking robot built at Carnegie Mellon University in Pittsburgh, Pennsylvania, that descended into the crater of an active Alaskan volcano, and the anthropomorphic Robonaut, designed at NASA's Johnson Space Center in Houston, Texas, to serve as a robotic assistant to space-walking astronauts.

But since then, NASA's support for general robotics research has waned. In the late 1990s, its then administrator Dan Goldin was more enamoured with biotechnology and nanotechnology. Programmes such as the space shuttle and the International Space Station were also getting into such fiscal trouble that no money was left for 'extras' such as robots. David Akin of the University of Maryland's Space Systems Laboratory recalls how these elements combined to cause a "perfect storm that destroyed robotics research at NASA".

At the same time, NASA's Office of Space Science narrowed its focus almost exclusively to building planetary rovers for the Mars exploration programme. The success of the current Mars rovers, Spirit and Opportunity, is undisputed. But their mission goals are much less ambitious than the new Moon–Mars programme will require. They are largely remote-controlled, and they focus on one fairly simple task at a time, such as taking a picture or drilling a rock. Given this pedestrian state-of-the-art, using

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construction robots to build a Moon base autonomously by a fixed deadline sounds like mission impossible.

So to meet its goals for human spaceflight, NASA will need to make robotics much more of a priority. History has shown that whenever the astronaut programme enters rough financial waters, robotics and other advanced technologies tend to be the first things thrown overboard. "The human spaceflight community is never thinking beyond the next mission," says Akin. Basically, NASA has always seen technology development as secondary to keeping astronauts safe and the shuttle flying.

Out of this world

As recently as 2001, for instance, NASA was short of money for the International Space Station, so it cancelled a test on the shuttle of Akin's robot, which was designed for in-orbit repair work. John Mankins, director of human and robotic technology for the new Moon–Mars programme, claims that this time, things will be different. He says that the agency has requested $115 million in next year's budget specifically for "technology maturation", which includes testing and flying robotic systems. But roboticists still fear that history could repeat itself.

Setting an ambitious goal like building a Moon base with little or no human intervention would focus NASA's diverse interests in the field, says Ken Goldberg, a robotics expert at the University of California, Berkeley. And the resulting research would foster technologies with far more application to everyday life than space shuttles and orbiting stations, which, Goldberg notes, have "very little spin-off for Earth".

Will says that there have been several NASA studies of potential lunar habitats, but little detailed consideration of how they will actually be built. To save the enormous expense of launching tonnes of raw material from Earth, it would be best to use lunar soil for habitat construction. And using astronauts as labourers makes little financial — or any other — sense. Machines would be needed to excavate the lunar material, melt it, mill it and fashion it into pieces for automated assembly. Designing such machines would push the frontier in every aspect of robotics, from autonomy to machine collaboration, Will explains.

The next generation of space robots will draw on mainstream robotics research under way in the United States, Japan and Europe. Commercial robots are getting more impressive every day, says Illah Nourbakhsh of NASA's Ames Research Center in Moffett Field, California. Sony's most recent version of its AIBO robot dog, for example, uses advanced algorithms for visual-pattern recognition to locate its battery recharger, even in unfamiliar settings — a key step towards autonomous operation.

Greater robot autonomy, including the ability to recover from errors without human assistance, will be crucial. When the Spirit rover froze on the martian surface in January, for instance, ground controllers had to shut down operations for several days and upload new software. This sort of intervention isn't going to be feasible for a large team of robots building a lunar base. "If you've got to coordinate 1,000 robots, do you have 1,000 astronauts doing it?" Will asks. "Probably not."

Tele-operation — having a human operator use a control device to direct the robot's movements remotely — is another possibility. But this is complicated by the several-second delay in sending radio commands from Earth to the Moon and back. The time delay becomes even more of a problem between Earth and Mars, making most experts argue that there is no substitute for autonomous operation.

Industrial robots operate flawlessly and autonomously because they repeat the same task in the same environment. Getting robots to collaborate on complex physical tasks, while moving around in a changing, unstructured environment, is much harder. Make that environment the lunar surface — with lower gravity, ubiquitous dust and other alien physical characteristics — and the problems begin to multiply.

State of independence

But progress is being made. Researchers such as Oussama Khatib of Stanford University in California are working out control algorithms that allow robots to collaborate with each other, and with humans, on tasks that might involve carrying bulky objects in unpredictable 'real world' environments. Teams at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, have got robots to grasp and carry a long beam together, and have developed a computer program that will allow robots to collaborate on simple tasks such as unpacking and deploying an array of solar panels. But these are baby steps compared with assembling a lunar base. Addressing that goal will require NASA's funding for robotics to increase by at least an order of magnitude, say experts in the field. Although that is a lot of money, it is still only a fraction of the tens of billions of dollars likely to make up the budget for the planned Moon–Mars programme.

Roboticists such as Goldberg would like to see NASA develop a broad, university-based research programme that includes Earth-based testbeds where engineers can rehearse new robotic techniques before heading to the launch pad. Building a Moon base is exactly the sort of challenge that would benefit from this approach. "Having a grand challenge, something that people could test their results on in a common framework, would be great," says Goldberg.

NASA's plans call for lunar missions as early as 2015, with a potential human flight

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If dreams of colonizing Mars are to come true, robots need to become efficient construction labourers.

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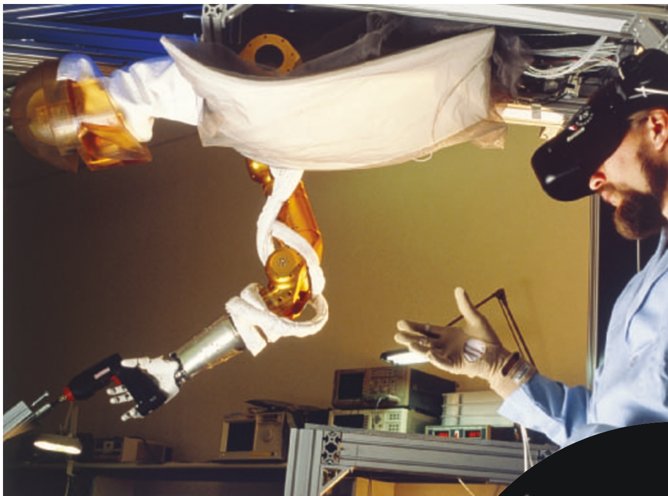
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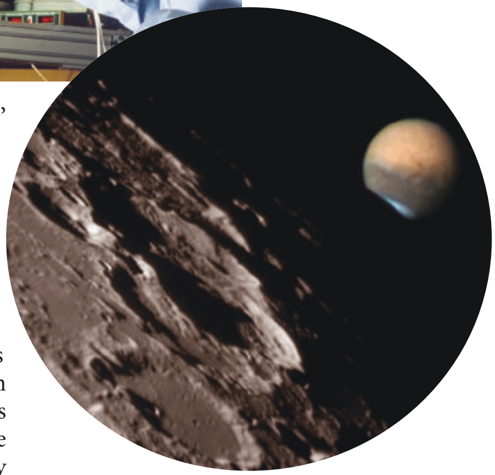
R. DANTOWITZ/CLAY CENTER OBS.

Bots and pieces: to explore the Moon and Mars (below), astronauts are going to need effective robotic assistants that are more autonomous than Robonaut (left).

to Mars a decade or so later. Before then, teams of robots for construction of the Mars base and resource extraction will have to prepare the way for human explorers. This next generation of space robots will need many new skills, but a quick glance at just one crucial feature — autonomous navigation — gives some idea of how much progress has yet to be made.

On Mars, NASA's most capable rovers have shown that moving around the martian surface is still agonizingly slow. "A future Mars explorer would be able to collect the same amount of material as Spirit and Opportunity have collected in two months in a single eight-hour work shift," NASA administrator Sean O'Keefe told a recent public forum. As a small step in that direction, JPL engineers have uploaded new software that allows the rovers to make more independent decisions on whether a stretch of terrain is safe to cross, increasing the distances they travel from a few metres to tens of metres a day.

Wild rovers

Encouragingly, robots have already travelled much farther and faster over similar landscapes on Earth. David Miller, a roboticist at the University of Oklahoma, has tested an autonomous, solar-powered rover called SR2 in the Californian desert. This rover can independently navigate distances of more than a kilometre with a single command from its human operators. Comparable distances have been covered autonomously by Carnegie Mellon's Hyperion rover in Chile's Atacama Desert. A next-generation rover named Zoe will return to the Atacama this spring to conduct biological investigations. The human operators will be at a base camp far away, just as they would be on Mars.

Meanwhile, NASA is making plans for a long-range Mars rover, scheduled to launch in 2009, that could roam over tens of kilometres. Nathalie Cabrol, a planetary scientist with the SETI Institute in Mountain View, California, says that fresh exploration strategies will be needed for long-range planetary rovers. For example, sampling a wider terrain means covering more territory, so it may not be feasible to stop at every interesting rock as the current Mars rovers do. Cabrol heads the science team for the Hyperion and Zoe Atacama expeditions, and is also involved with the current Mars rovers. Hyperion's last trip to the Atacama showed how scientifically productive a long-range rover can be. Using only data from the rover, scientists back at Ames Research Center characterized the local geology with an "astonishingly high" level of accuracy, she says.

While NASA's planetary rovers make steady progress, research into autonomous robotic exploration has received a welcome boost from the US Department of Defense. Military interest in autonomous navigation stems from a need for vehicles that can cross behind enemy lines with no humans onboard. The first Defense Advanced Research Projects Agency (DARPA) 'grand challenge' for fully autonomous ground vehicles, a 228-kilometre race between Los Angeles and Las Vegas, ended last month almost as soon as it began. No vehicle got more than 12 kilometres from the starting line, but roboticists hope that the attention generated by the race will spur the development of their field.

Roboticists were not surprised, or disheartened, by the outcome of the challenge — few expected any team to finish the course. Carnegie Mellon's Sandstorm vehicle, the one that travelled farthest, averaged an impressive 15 miles per hour before breaking down, and the team is already tweaking its navigation algorithms in preparation for a second race in October 2005.

In the meantime, robots may get the chance to prove themselves in an arena where astronauts traditionally have excelled — repairing the Hubble Space Telescope. In the wake of the loss of the space shuttle Columbia last year, NASA has decided that sending astronauts to service the telescope a fifth time is unacceptably risky. So it has asked for ideas on how the next servicing mission could be done robotically (see *Nature* **428,** 353; 2004).

Soldering on

Akin's team at the University of Maryland has long been developing robots for that very assignment. His NASA-funded devices, called Ranger and HERCULES, are equipped with arms and interchangeable tools, and can be remotely controlled by humans or left to work autonomously. In extensive underwater tests conducted since the 1980s, Akin has shown that the robots can assist spacewalking astronauts during simulated Hubble repairs, and even save significant amounts of time. When he broke down the tasks for the 2002 repair mission, Akin found that the astronauts performed 1,860 discrete activities, 82% of which could have been done by a robot using simple tools. With more complex tools, all of the tasks were within its capability.

Neither of Akin's systems has flown in space. And the plan was always to test them working alongside astronauts first. Turning over the entire repair mission to a robot raises the stakes even higher, but is still feasible, Akin believes.

The success of such a high-profile mission could give NASA managers the confidence they need to push robots into more demanding roles within the Moon–Mars programme. Mankins says that the agency fully understands the need to blur the line between manned and unmanned technology — a distinction that in the past has ghettoized robotics, leaving the field vulnerable to budget cuts.

This time, funding for basic research is not optional. Even if the rockets and the life-support systems absorb most of the projected $60 billion for a human Mars mission, that should still leave several billions for robotic technology development.

"If we're going to put people in space, they're going to have to be surrounded by really smart instruments," says Will. ■

Tony Reichhardt writes for *Nature* from Washington DC.

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