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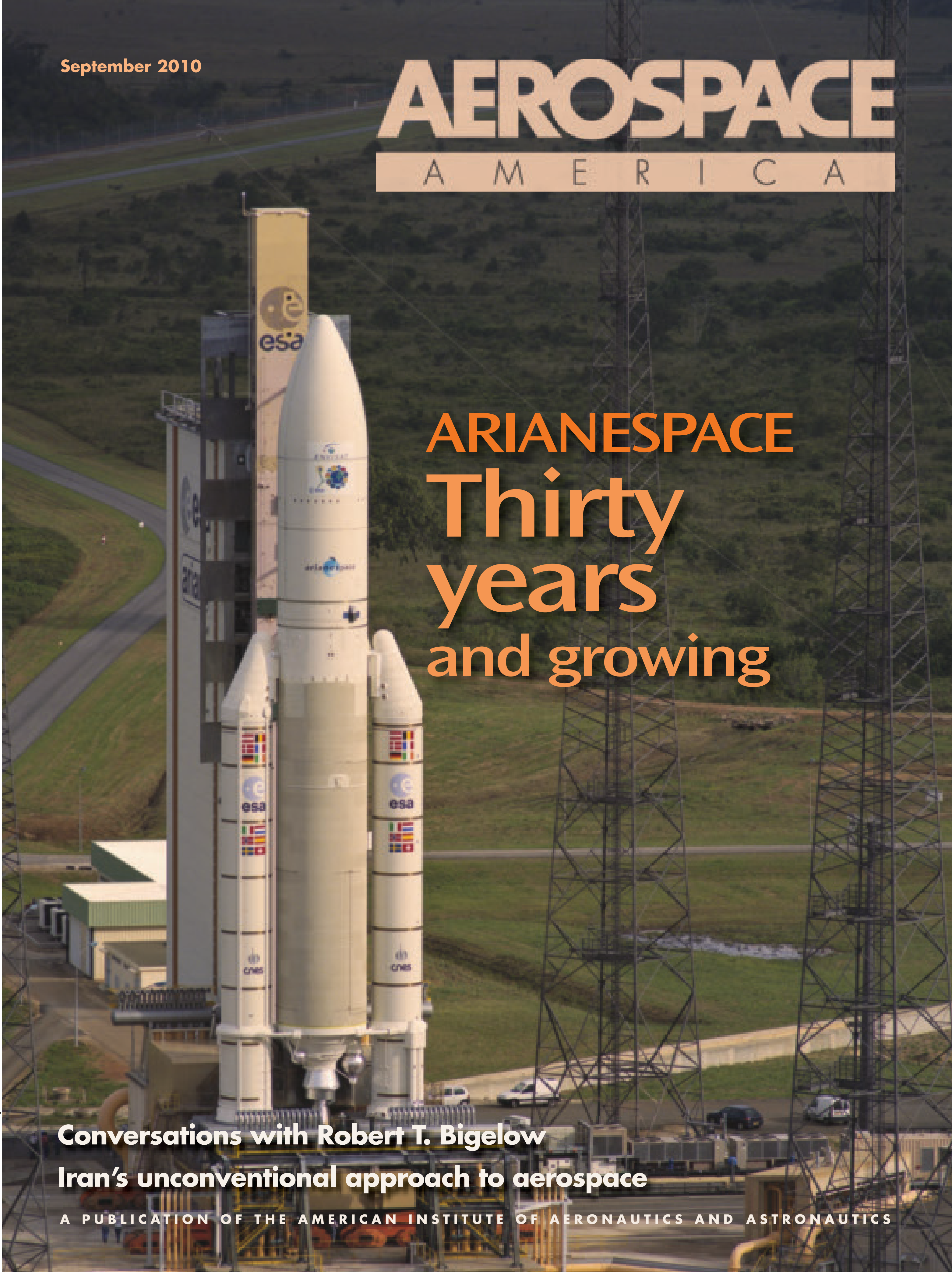

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When NASA's new R2 (for Robonaut 2nd Generation) arrives on the space station, it will do something no other humanoid robot has ever done—perform useful work, side-by-side with human astronauts in space.

The similarity in name to Star Wars' famous R2D2 is purely coincidental—indeed, R2 is closer in appearance and capability to the movie robot's sidekick, C3PO. Except this R2 does not speak. Yet.

"This version does not have the same voice synthesis capability we had on the original [R1], but we can do that," notes Nicolaus Radford, Robonaut deputy project manager at NASA Johnson.

"We do a lot of nonverbal communication with the way the robot can gesticulate, based on research from DARPA showing you can point and the robot can develop a response as to what you mean. However, this program was primarily looking at how NASA and General Motors [Robonaut prime contractor] come together to further the state-of-the-art of humanoid robots that will work around people. So our main focus was really developing the manipulator and dexterity portions of that first."

by J.R. Wilson
Contributing writer

R2, soon to be launched to the ISS, will become the first humanoid robot to do useful work alongside astronauts in space. Developed by a NASA/General Motors team, R2's advanced features will enable it to perform increasingly difficult tasks both in space and on GM's shop floor. Team members say the two organizations' differing needs and perspectives have sparked innovation and even helped to speed progress.

"Both speech recognition and response would increase the robot's capability, absolutely—and that already is part of the game plan," says John Olson, director of the Exploration Systems Integration Office at NASA Headquarters. The obvious benefit, he says, is that the human could deliver simple instructions or requests. "So the goal for future development is hearing first, then speaking."

Mobility: It's complicated

At present, R2 has only an upper body—torso, head, and two arms, with the most advanced mechanical hands and fingers yet developed. In null gravity inside the ISS, legs are unnecessary. But mobility, beyond simple floating, is part of the Robonaut's future, both in space and on Earth, where GM sees it as a major addition to its manufacturing plant workforce. "We see a dominance of applications that do not require mobility….But there are applications where we can take advantage of it," says Alan Taub, GM vice president for global R&D.

Mobility also raises major complications for the robot's programmers: It is one thing to enable R2 to pick up a wrench and tighten a nut—it is far more complicated if the robot is

"You just keep plowing ahead until incremental successes aggregate into a technological leap."

Nicolaus Radford,
deputy project manager-Robonaut, NASA Johnson

walking or rolling toward the nut while reaching out with its arm and manipulating the wrench in its hand.

"Once I have allowed the torso to move, I get extra complications in getting coordinates aligned between what is seen and touched. There are a lot of algorithm and math challenges to overcome to allow fine motor skill operations if the torso has major large-scale movement," Taub says.

The first "leg" fitted to R2 will likely be a grappling element that would enable it to move along the outside of the space station and lock itself down while leaving its arms free. By using power plug-in points already in place for Dextre, the station's existing external, albeit nonhumanoid, robot, R2 could keep itself fully powered.

In an EVA mode, R2 also could get into tight spaces where a human astronaut in a bulky spacesuit could not fit. But R2's first duties will be inside the ISS.

NASA and GM, although working toward some common goals, have decidedly different futures in mind for the humanoid robot. Both see R2 primarily as a partner to humans, doing jobs that are too dull, dirty, or dangerous for far more expensive—and fragile—human beings. But government and industry officials are quick to say that although robots may take over some tasks, they will not replace their biological masters.

Robonauts built for space and those built for automobile assembly plants have much in common—and a great many differences.

Spacefaring humanoids

R2 and its successors will face significant tasks working inside and later outside the ISS. But NASA also has long-term plans for Robonauts to prepare initial sites for human missions to the Moon, Mars, and other destinations.

"As we look out 5, 10, 20 years, I think we will see some amazing capabilities," notes Olson. "But that is couched in the sense of better developing synergy between humans and robots, not one replacing the other."

Robots will first be assigned simple but essential tasks that do not really need the human touch. "The nice part about Robonaut is it can use the tools we have designed for humans and leverage existing hand restraints. ISS is sized to human dimensions, so having the robot fit into those is added utility," Olson says. "As its capabilities and our comfort with it evolve, so will its tasks and utility."

Safety is a primary focus of the Robonaut program, and is also among the most difficult elements to achieve. It is essential in space, where medical attention for astronauts is limited, but is of no less importance on a terrestrial manufacturing floor.

"This program was designed from the get-go to have humans and robots working in close interaction. For example, if you bump into R2, it is compliant, unlike other robots," Olson says, referring to its ability to give way to a human. "It also is designed to sense proximity and location, so it has been optimized for a close working environment, revolutionizing the way humans and robots interact.

"In every element of our missions, training has safety as a critical element. Inside the ISS, part of the profile is to expand our comfort zone and human/robot interaction. R2... can detect the presence of a human, which impacts its algorithms appropriately."

There are obvious advantages in interplanetary missions to sending robots ahead to prepare a landing site, locate water and other local essentials (such as useful metal ore), build initial habitats, even start gardens to provide food and oxygen and remove carbon dioxide. But that advance guard need not—probably will not—be humanoid.

"Do we need a humanoid robot to go to those places or would another type serve, either with better, lighter, or different mass or volume? The question is, what are the needs of those missions?" Olson explains. "The humanoid shape of R2 allows it to use a lot of the same tools if we plan to send humans or if they already are there. But if we are sending the robot there first, it doesn't have to have a humanoid shape."

Advanced features

Radford says R2 already demonstrates a number of significant advances over R1. Many have been combined, shrinking it to nearer human size and enabling it to function far more quickly. Employing force-torque rather than position-controlled manipulators allows greater variance in the forces used when R2 interacts with people. It has the world's most advanced sensors and sensing capabilities, especially in its fingertips.

"We have a lot of actuator and motion controller development. It doesn't do you any good to have the world's greatest sensing robot if you can't resolve those forces into action," says Radford. Using its sensory data and turning it into joint motions "takes a significant amount of processing power. So we have a hierarchy of embedded processors distributed all around the robot that are able to process the sensors at a very local level to enact a control methodology.

"In the original Robonaut, we had bus cables and sensor wires on hundreds of conductor levels back through the arms to a central processor. On this robot, we have a single bus network, a high-speed communications bus, with a very small number of wires, because we do all our joint processing locally in each actuator. That was a main design requirement, to reduce the number of wires, because wires tend to propagate failures. So this robot was designed from a maintenance and serviceability point of view, on which GM had a considerable amount of influence."

What distinguishes Robonaut from all other robots, he adds, is the use of a series of elastic actuators for manipulation.

"We have a rotational, torsional spring on the outside of all our gear trains, our joints, and sense the positional differences of that spring and resolve that into torques, which we can measure very finely and turn into control methodology for the robot.That is what gives it its unique control so it can interact with people in a way a positional robot cannot," Radford notes.

"We have a bunch of FPGAs [field-programmable gate arrays] for our distributed processing—about 25 with dual Power PC processors each—which form the backbone of the robot's motor control." This is "similar to a human spinal column, where a lot of low-level reflexes are handled locally rather than going back up to the brain. That allows us to run very high speed control loops—torque control loops at 10,000 Hz at each joint level, which is the highest we know about.

"We have a lot of sensing in the hands, including the world's smallest six-axis load cell in the fingertips, a customized load cell we invented here at JSC that exists in all the fingers, so it has a very good idea of how it touches things. Tactile feedback was paramount on this system; we wanted it to have a very fine touch....So the palm has its own processor, taking all the data from the fingers, computing necessary actions and sending the relevant information back upstream to the bigger processors."

All of this is also important to GM as it looks to the Robonaut concept for terrestrial manufacturing. And any success R2 and its successors have in building cars can transfer to similar tasks in aerospace manufacturing.

Gravity and other issues

There is one aspect of development that, although of little or no interest to GM, is critical to NASA, and that is gravity.

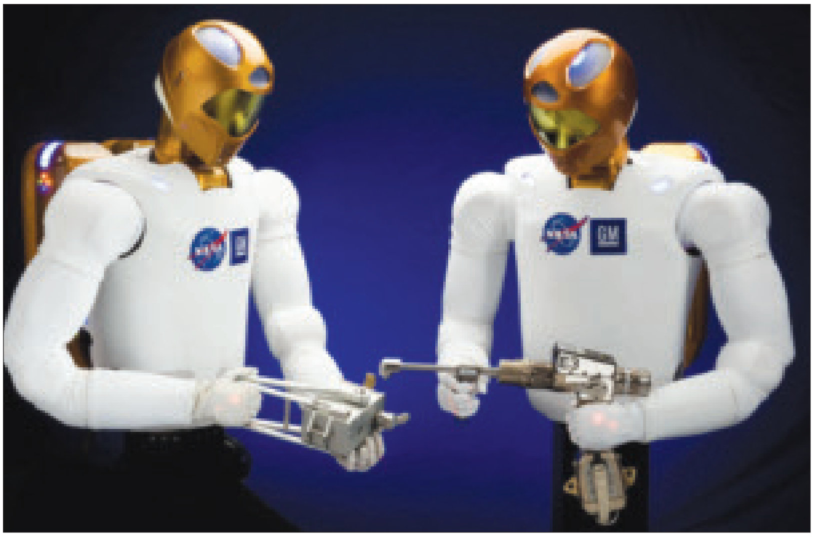
"We have an array of tasks we have developed in a 1-*g* environment. First and foremost, we want to re-prove those in space, because robot control will be a lot different in 0 *g*," Radford says. "There is a lot of control involved with this robot that takes into account the effects of gravity. To see what happens in that environment, we are flying a task board along with the robot with a lot of common-use tools and connectors. Those represent things the crew has to perform on orbit; it will demonstrate how the robot can interact with a lot of ready, available things on the ISS."

Earlier robots in general have been "really bad at working with floppy materials," notes Radford. "This robot handles those very well," a major design goal. "We have a lot of soft goods on the space station, so we see a future use of this robot in handling a lot of those soft materials that have to be removed in order to access what is behind them."

UAW robot guild?

In the 1970s and 1980s, one of the first advantages Japanese industry employed to over-

R2 was designed to use the same tools as humans, which allows them to work safely side-by-side with humans.



take America's Big Three automakers was the industrial robot. By replacing humans with robotic welders and painters around the clock, Toyota and others were able to speed up production, enhance quality, and cut costs.

Detroit responded by bringing in robots of its own—a difficult task, because the assembly line essentially had to be built around them. However, humanoid robots such as R2 can move into an existing facility, use its tools and procedures—and do so much more safely than a multiton welding robot could.

"When a big robot is doing its routine, it will head to where it needs to go whether a human is in the way or not," says Radford. "Most factories spend more money protecting the workers from robots than on the robots themselves." This led to developing "the impedance-controlled manipulator, which allows R2 to interact with humans in a very safe way."

Susan Smyth, director of manufacturing systems research at GM's Manufacturing Assembly & Automation Center, says success is a combination of equally important factors such as safety, reliability, human comfort in working alongside a humanoid robot, and ease of maintenance.

"It's one thing to have a mechanism that performs a number of tasks in a controlled environment. But when you try doing that task 100,000 times, with people around it, a much greater level of physical robustness is required," she adds. "So having a really robust electrical system going forward is a big thrust."

Seeing and feeling

"In robotics today, you find a lot of talk about vision and sensors. But the challenge is sensor fusion," says Roland Menassa, GM's manager for advanced robotics. "Humans use many different sensors—when vision is occluded, you can rely on touch. We've done the same with the Robonaut.

"It is the interplay between sensors that makes possible the handling of flexible parts. And fundamentally, what makes that possible is the miniaturization of a lot of the componentry and high-speed computing. You can embed that technology just about anywhere you want."

Taub cites one of the challenges GM gave Robonaut: Installing a floppy sheet of rubber into a precise location on the inside of a car door to protect it from water.

"In the past, robots in our plants could barely deal with solid pieces of metal. That was solved only about five years ago. So now we have two arms, operating semiindependently, pulling on fragile pieces without ripping them," he says. "Second, you have to find precise locating points—one of which can only be identified by feeling a bump on the part—then insert that locating point into a part on the vehicle it has to find by vision. So R2 had to find a part by feel, using robotic fingers, then deal with what it was holding using mechanical vision.

"In the end, the robot was able to do all those things. The only limit is it is slower than a human, but the fact it could do all three in a demonstration project says this robot can basically handle ergonomically difficult, highly repetitive operations in the plant."

Testing period

Testing R2 inside the ISS will provide an important intermediate environment between Earth and extravehicular space. There the robot will be subjected to microgravity and to the radiation and electromagnetic interference environment of the station.

"Our goal is for R2 to perform routine maintenance tasks, freeing up the station crew for more important work," explains Ron Diftler, Robonaut project manager at NASA Johnson. "Here is a robot that can see the objects it is going after, feel the environment, and adjust to it as needed. That is pretty human. It opens up endless possibilities."

The ground team and the ISS crew will control the robot with identical systems, each comprising a graphical user interface on a computer screen and pushbutton navigation.

"R2 operates under 'supervised autonomy,'" says Diftler. "It can think for itself, within the limits we give it. We will send it scripts—sequences of commands."

The interior operations will provide performance data about how a robot may work side by side with astronauts. Then it will slowly progress from simple tasks, such as monitoring its own health, to more complicated assignments. As development activities progress on the ground, station crews may be provided hardware and software to update R2 and enable it to perform new tasks.

The Robonaut project also seeks to develop and demonstrate a robotic system that can function as an EVA astronaut equivalent. Robonaut jumps generations ahead by eliminating the robotic scars (special robotic grapples and targets) and specialized robotic tools of traditional on-orbit robotics. However, it still keeps the human operator in the control loop through its telepresence control system. Robonaut is designed to be used for EVA tasks that were not specifically intended for robots.

R2 is undergoing extensive testing in preparation for its flight. Vibration, vacuum, and radiation testing along with other procedures being conducted on R2 also benefit the team at GM, who plan to use technologies from R2 in future advanced vehicle safety systems and manufacturing plant applications.

Edward Flinn

Taub also says GM sees the coming generations of factory robots as augmenting their human partners, not replacing them. Indeed, manufacturing improvements and cost savings brought about by robots such as R2 may lead to more sales, more plants, more jobs.

Benefits of partnership

Factories also could take the lead in developing mobility for R2, as they are likely to need that capability sooner than NASA will.

"Our plan is to enhance our current robots," says Taub, noting that they are "still experimental, expensive, and not robust; so it will be awhile before we see a full Robonaut on the plant floor. "We can get 80% of the benefit of a humanoid robot just with a world-class torso….But in parallel to developing a hardened version of Robonaut, we will be working on a not-yet-announced initiative to make it mobile."

Eventually, the GM/NASA partnership will expand further.

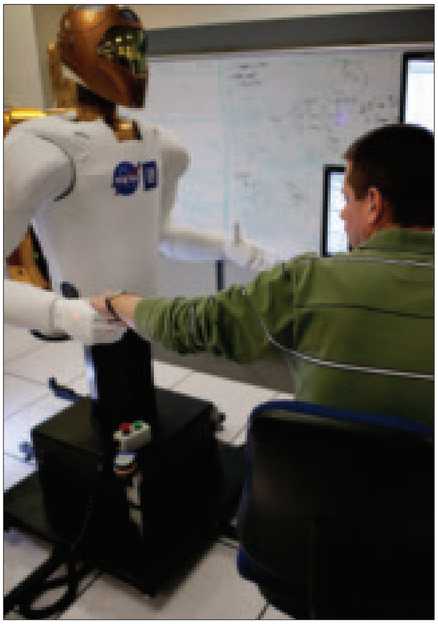
"Breakthroughs in technology and applications used to come from multidisciplinary teams in a given organization. But R2 has demonstrated the value of crossing industries and application space," Taub explains. "For example, GM and Boeing have a 50-50 ownership for a lab in California where we do research at the intersection of aerospace and automotive. One of the Robonaut team members came from that lab.

"It might seem difficult to meet the needs of two different industries….But the surprising thing is, even though you end up putting higher requirements on a joint project, a team bringing different viewpoints and backgrounds to resolve challenges unique to both actually moves faster. The innovations come from the team looking at the problem from two different perspectives.

Those perspectives are colored by the roles they see humanoid robots performing in their particular environment. But basically they all come down to turning one of the oldest science fiction dreams into reality.

From the perspective of scientists and engineers, Robonaut represents a coming together of multiple enabling technologies in ways that would not have been possible any earlier.

"As I look at the technology breakthroughs, it was fundamentally a biomimetic force system, using a tendon-like actuation mechanism, a terrific job of miniaturization of components to get size and moment of inertia down; then some very critical intellectual property around how to make forcing systems compliant, and the sensors around that," concludes Taub. That combination produced "a robot capable of lifting heavy weights and doing real work, but with the compliance of a human. Now superimpose extra sensors so we can get predictive capability."



The 300-lb R2 consists of a head and a torso with two arms and two hands.

Forward steps

Menassa sees R2 as the first of many generational leaps to come. "R2 is really a giant step forward, designed from the onset to mimic human motion, size, and speed…." The compactness of R2 is truly a testimonial to the technology that went into making it. But we also had to do advances in controls actuation and human/machine interface, so you can interact with the robot the same way you would with a human."

For many of those involved in the development of Robonaut, the future of humans and robots is inextricably linked.

"This project exemplifies the promise that a future generation of robots can have, both in space and on Earth," Olson notes. "The combined potential of humans and robots is a perfect example of the sum equaling more than the parts. It will allow us to go farther and achieve more than we can probably even imagine today."

"This is the opposite of technology replacing humans; rather, [it is] fundamentally enhancing the ability of an individual human or a system of humans and machines working together."

Susan Smyth, director,
manufacturing systems research,
GM Manufacturing Assembly & Automation Center