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DESERT RUNNERS

LIZARDS, CRABS, AND COCKROACHES ARE SHOWING RESEARCHERS HOW TO BUILD THE ROBOTS THAT WILL SOMEDAY SCURRY ON THE SANDS OF MARS

THE 10 BEST HIGH-TECH CARS

THE UNIVERSAL CELLPHONE HANDSET, SOFTWARE DEFINED

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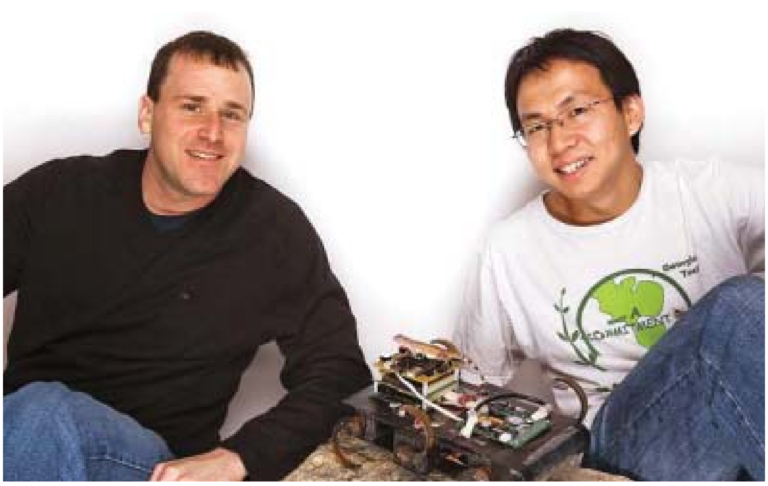
back story



Running With Robots

How hard can it be to make a lizard run? Just ask the researchers in Daniel Goldman's laboratory at Georgia Tech. "It's very high tech," says Goldman [left]. "We startle it."

They wave bits of cardboard, flash lights, and gently pinch the lizards' tails. Then they do it again. And again. And again. "Sometimes I try to make a noise, but that doesn't seem to work," says Chen Li, a physics graduate student [right].

The 65 lizards, crabs, and cockroaches in Goldman's lab can be ornery companions to the one robot that beats a steady path down a track in the lab. In "March of the SandBots," Goldman and his colleagues explain how they invested in that robot the tricks they'd learned about sand scampering from the finest desert runners on the planet.

But building a bio-inspired robot can involve a few odd negotiations. To acquire some of the creatures in Goldman's menagerie, one student coaxed collectors in the Middle East into selling their prized Egyptian desert cockroaches (*Polyphaga aegyptiaca*) for about US $10 a bug.

Goldman, too, contributes a catch or two. He grew up chasing ghost crabs on the sandbar islands of North Carolina and five-lined skinks around his home in Richmond, Va. At the age of 10 he learned how to snag one of those lizards: He'd dangle a coil of rope on a pole and stand several steps from his target. Then he'd lower the noose around its neck and pull up, ensnaring the thrashing skink and delivering it unharmed to a cloth bag.

But unlike lizards in the wild, captive animals can be exhaustingly placid. "I can say, 'Animal, go!' or 'Animal, move your legs in a certain way,' and it won't do that," Goldman reports. Indeed, an annoyed ghost crab may instead go on the offensive, snapping its claws energetically at its appointed frightener.

Li, who grew up watching animal documentaries in China, hadn't anticipated how unpredictable the animals would be. So when it's the robot's turn to strut, the physicists breathe a sigh of relief. "The robot gives us data that's more repeatable," Li says. "It's very nice." ❑

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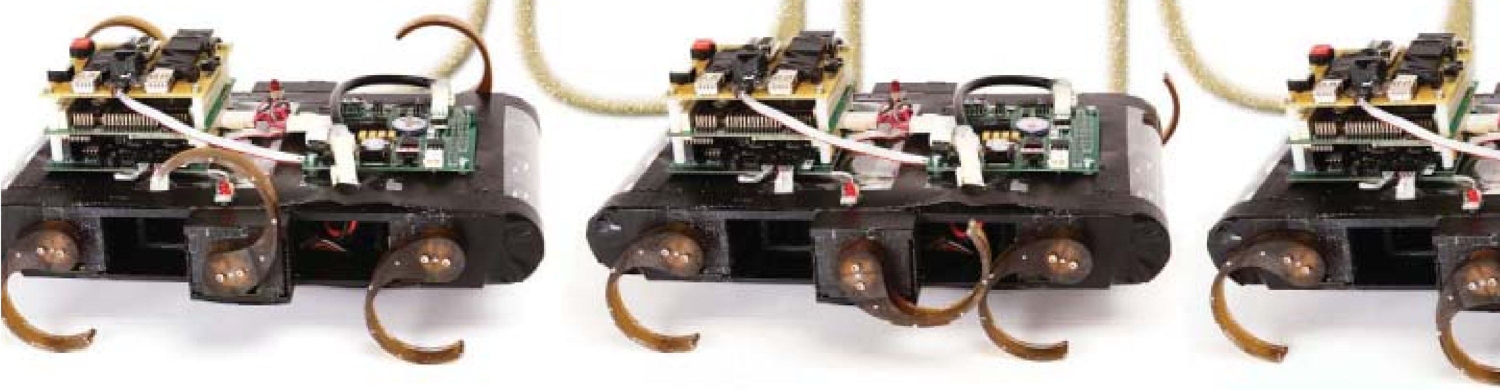
MARCH OF THE Sand



A new generation of legged robots will navigate the world's trickiest

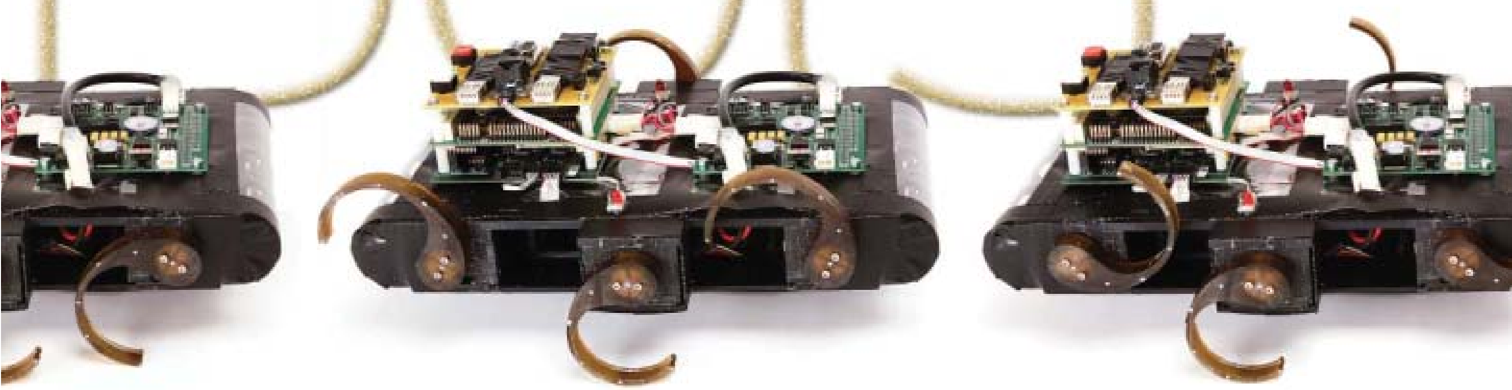
A ZEBRA-TAILED lizard stands on a bed of tiny glass beads and shifts its weight. The beads slip underfoot, and the mottled beige creature stretches its spindly toes to get a better purchase. Suddenly it breaks into a run, blazing across the granular surface with stupendous agility, its toes stretching out flat as they hit the beads, its feet whipping back and forth in a blur. Each side of the lizard's body stretches and then coils in turn as the reptile darts ahead at several meters per second.

Scooped up a year ago in California's Mojave Desert and transplanted to a lab at Georgia Tech, the lizard holds our interest because of its truly peculiar feet. Those long, bony toes allow the reptile to navigate over sand, rocks, and the many other types of terrain it may face in the desert. In the lab, the bed of glass beads stands in for desert sand, and by blowing air through it or packing it down, we can make the ground looser or more solid. We then study how the lizard copes with the changes.

Our interest isn't purely biological. We—Goldman at Georgia Tech, Koditschek and Komsuoglu at the University of Pennsylvania, in Philadelphia, and our other collaborators—are hoping that by studying the zebra-tailed lizard and a menagerie of other desert-dwelling creatures, we can create more agile versions of our six-legged robot, SandBot. When traversing solid ground, the robot runs at a steady clip of two body lengths per second. (For comparison, a trotting dog covers four body lengths per second.) But on its first outing across the glass beads, SandBot dug holes fruitlessly with its crescent-shaped feet and got stuck after just a few steps.

Sand, it turns out, is one of the most difficult terrains for a robot to conquer. Sand is slippery, for one thing, and it is also inherently unstable: Its properties can easily flip between solid and fluid behavior in the course of a single footstep. Physicists still don't have a complete picture of the mechanics of sand, which is why we've turned our attention to the lizard and the clever strategies it has evolved to cope with sandy terrain. For example, we have noticed that the lizard's long toes sink deep into the sand at each step. It appears that this allows it to push off from sand that's deeper and more solid than the less stable surface layer. The

Bots



terrain By Daniel Goldman, Haldun Komsuoglu & Daniel Koditschek

effect, preliminary evidence suggests, is that the sinking enables the lizard to run as if on hard ground, allowing it to maintain speeds up to 75 percent of its pace on solid ground. Desert animals deal with sand with different levels of success, and their techniques provide valuable clues for refining SandBot.

Ultimately, we would like to build robots that can traverse any kind of terrain—bounding across hard ground like a gazelle, scaling tall trees and buildings like a squirrel, or maneuvering over slippery piles of leaves or mud like a snake. At least for short periods, a few robots already have managed to scale vertical walls, leaf-covered slopes, and even ice. Eventually, highly mobile robots could make a big difference in search-and-rescue missions and could explore all kinds of tricky terrain, not just on Earth but on the moon, Mars, and beyond.

First, though, our machines need to conquer sand. Had we been designing a wing for flying or a flipper for swimming, we would have been guided by the well-established rules for fluid flow, the Navier-Stokes equations. But for a complex material like sand, the equivalent models do not yet exist. So we had to start at the very beginning, by investigating the physical properties of granular materials. After about two years of study and experimentation, we in our small consortium of physicists, roboticists, and biologists think we have identified some basic rules describing movement across granular surfaces. Applying that knowledge to designing sandworthy robots, though, is not at all straightforward.

Consider how humans transport themselves over land. In places where massive investments have been made in roads and tracks, it's relatively simple to move about by car or train. In fact, our vehicles require all of that engineered smoothness—without it, they can't go far. But much of the Earth's surface is largely inaccessible to vehicles, including robots. About 30 percent of the land area is desert, and one-fifth of that is covered by some kind of sand.

Sand isn't the only issue. Disaster sites and battlefields—precisely the places where mobile robots are expected to be most useful—are full of unpredictable, impassable rubble. In 2001, for example, robots were sent in after the World Trade Center towers collapsed, but debris quickly clogged their tracks or caused

ALL PHOTOS: YVONNE BOYD

the robots to flip over. Likewise, when a coal mine collapsed in Sago, W.Va., in 2006, a rescue robot made it about 700 meters past the mine's entrance before getting stuck in mud. Even benign stuff like gravel and fallen leaves can stop a robot cold.

In short, robots that navigate on wheels and tracks are nearing their performance limits. Legged robots that mimic the movements of insects or animals offer a promising alternative, but figuring out the mechanics of walking hasn't been easy. Because not much is known about how the forces between a foot and the ground interact to create movement, the prevailing method for designing these robots has been essentially trial and error: Build the machine and hope for the best.

But we've come a long way. The first computer-controlled legged robot dates back to the 1960s, when Robert McGhee's Phony Pony took its first halting steps at the University of Southern California, in Los Angeles. McGhee then followed up on that project at Ohio State University, in Columbus, creating the first autonomous legged robot in 1976. This machine, known as Hexapod, could make its way slowly across some wooden blocks indoors.

A decade later, McGhee and his colleagues' 5-meter-long Adaptive Suspension Vehicle was the first autonomous legged machine to tackle the great outdoors. Moving ponderously at a fraction of a body length per second, the robot carefully placed each leg and then torqued its joints to generate the necessary ground-reaction forces to push its body forward.

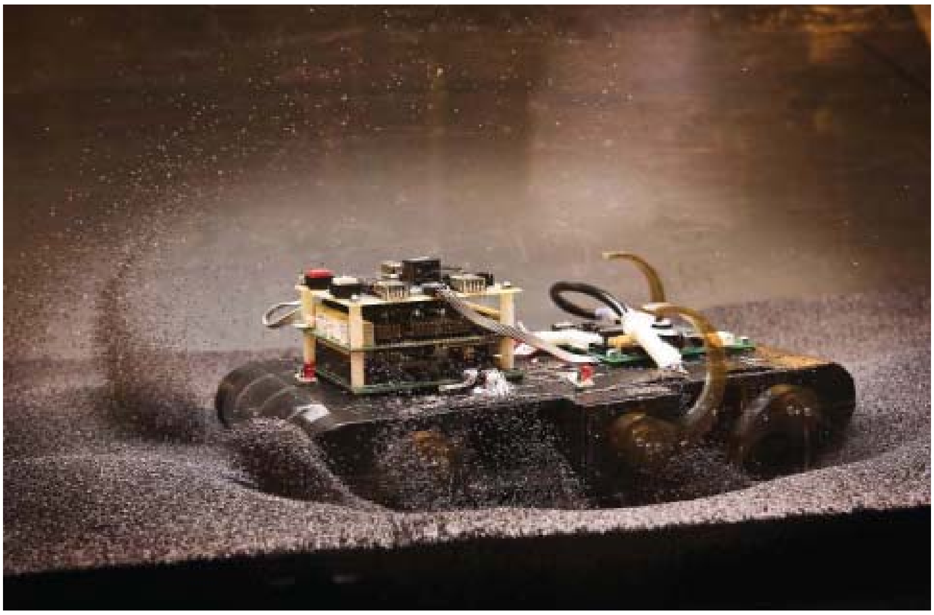
The next phase in legged robots was ushered in with the dynamically dexterous machines built by Marc Raibert at Carnegie Mellon University, in Pittsburgh, and later at MIT. Dynamic dexterity is the ability to exchange potential energy and kinetic energy in a controlled manner—or the difference between a hopping kangaroo and a car. A kangaroo's bent legs store potential energy, which allows it to bound effortlessly over obstacles. The ability to direct its body's flow of mechanical energy is critical for a robot to navigate unpredictable terrain. Raibert's creations were essentially self-excited pogo sticks that used springs to balance, hop, and when yoked together, trot and bound. These robots still hold the ground speed record of 21 kilometers per hour, but they were strictly designed for controlled laboratory environments.

The RHex robot, designed by the roboticist Martin Buehler (then a professor at McGill University, in Montreal) and Koditschek's group in 1999, took running robots to the next level. This autonomous machine, inspired in part by integrative biologist Robert Full, of the University of California, Berkeley, has six legs that are attached outside its center of mass. This sprawled configuration grants the robot greater stability as it bounces over natural terrain. Faster runners have since appeared, but RHex remains, to our knowledge, the only legged machine that can traverse rugged, broken ground rapidly—at or above the pace of one body length per second.

RHex in turn became the model for a family of robots whose appendages are each driven by a motor located at the hip. Its progeny include, among others, the Aqua robot, which is basically RHex with flippers for swimming; a two-armed, wall-climbing robot named Dynoclimber; and SandBot.

In early 2007, Komsuoglu designed and built SandBot in less than a month, using the RHex model and a modular infrastructure of his own creation [see "Seeing Inside SandBot"]. At 2 kilograms, it is less than a quarter of the weight of RHex. Like RHex, SandBot has six compliant, independently controlled legs, each of which is a semicircular strip of plastic. Also like RHex, it walks with an "alternating tripod" gait, inspired by insects. The legs move in threes, with the front and rear leg on one

REGOLITH RUNNER: SandBot trundles down a track filled with poppy seeds, in preparation for the many kinds of dust, sand, and loose soil it will eventually encounter outside the lab.



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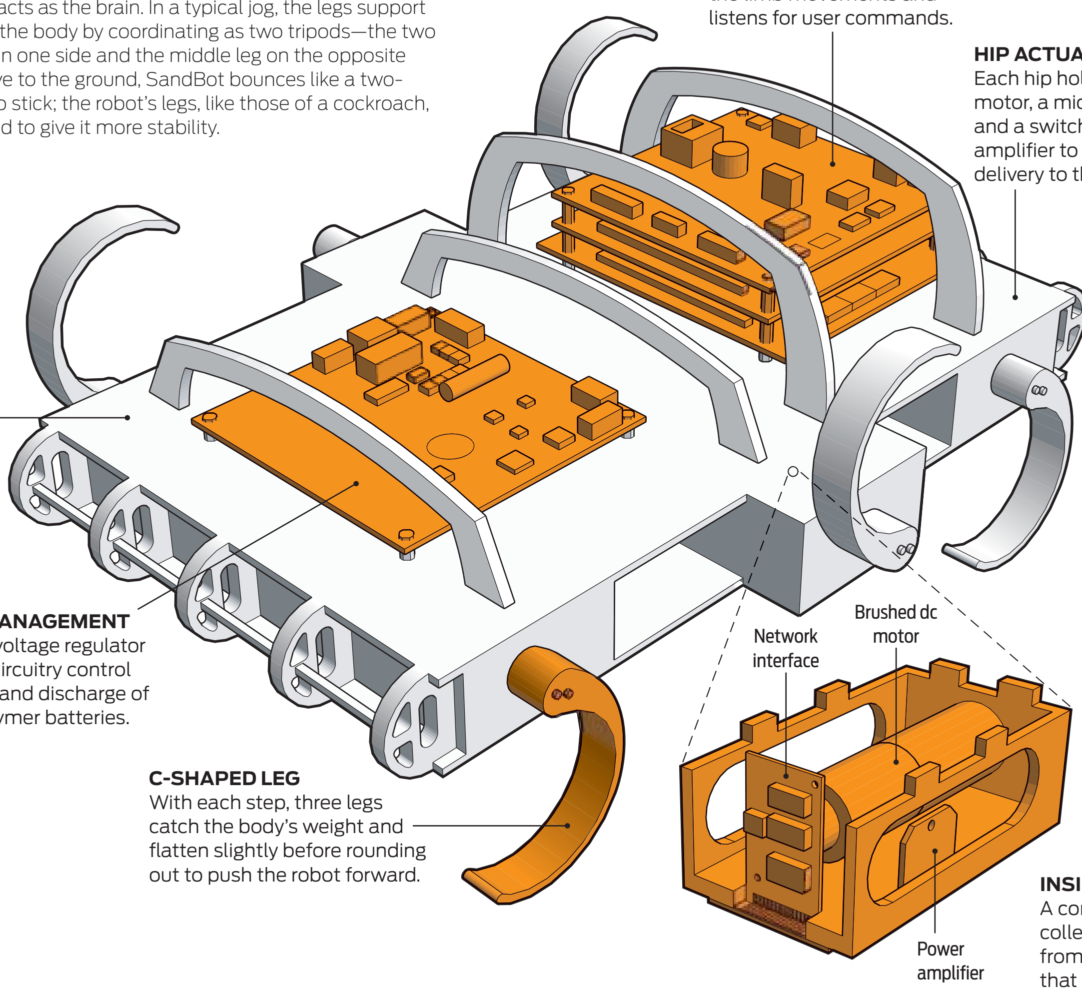
Seeing Inside SandBot

SEVERAL BODY parts interact to allow SandBot to scurry over slippery grains. At the center is a computer that acts as the brain. In a typical jog, the legs support and propel the body by coordinating as two tripods—the two outer legs on one side and the middle leg on the opposite side. Relative to the ground, SandBot bounces like a two-legged pogo stick; the robot's legs, like those of a cockroach, are sprawled to give it more stability.



CENTRAL PROCESSOR The "brain" coordinates the limb movements and listens for user commands.

HIP ACTUATOR Each hip holds an 11-watt motor, a microcontroller, and a switching power amplifier to regulate power delivery to the motor.

RIGID PLASTIC SHELL

POWER MANAGEMENT BOARD A voltage regulator and other circuitry control the charge and discharge of lithium polymer batteries.

C-SHAPED LEG With each step, three legs catch the body's weight and flatten slightly before rounding out to push the robot forward.

INSIDE THE HIP A controller collects data from sensors that monitor leg position. The controller also translates high-level commands from the central processor into limb motion.

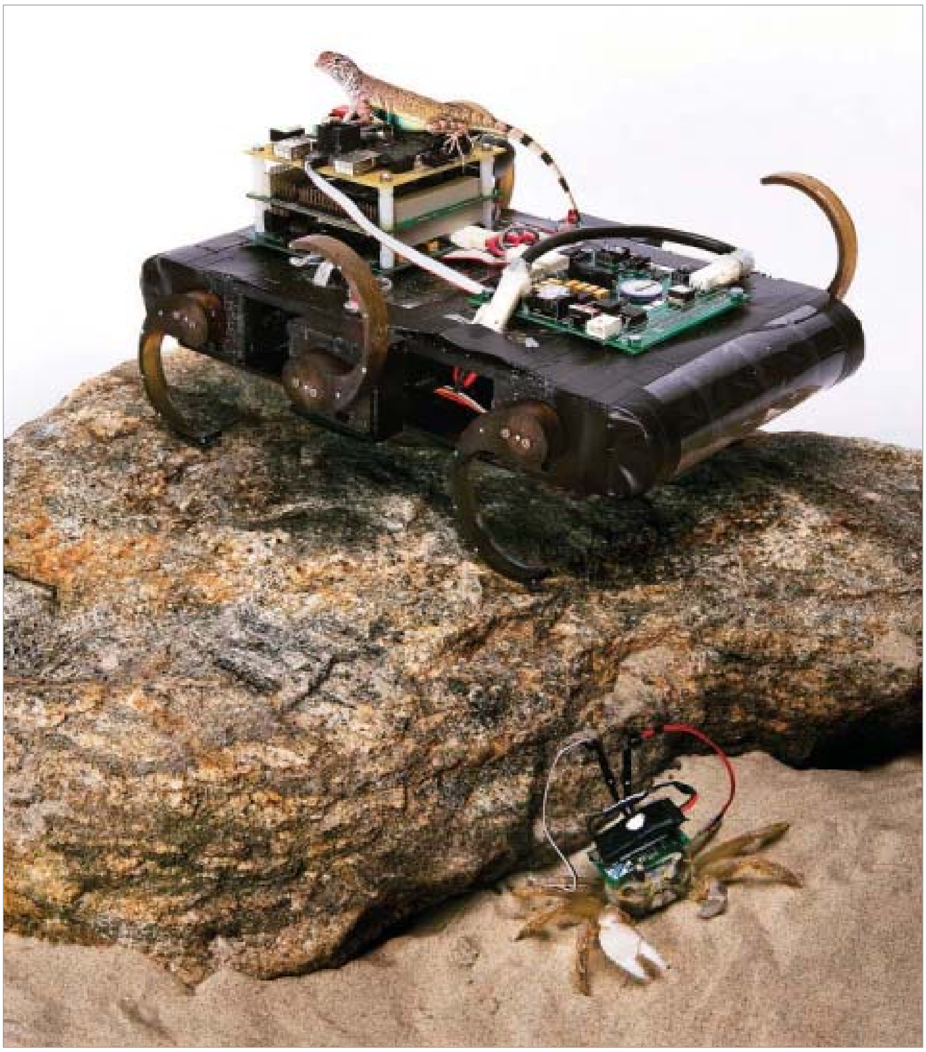
JASON LEE

side moving in sync with the middle leg on the opposite side. The two tripods alternate supporting and propelling the body, then circle around after each step.

On the inside, SandBot is composed of modular nodes that communicate through a real-time network called RiSEBus, inherited from an early version of its climbing sibling. At the hip joint of each leg sits an 11-watt brushed dc motor driven by a custom-designed motor controller board with a quadrature encoder, which senses the position of the motor's shaft and therefore the angular position of the leg. The six motor controllers link to a central computer, which functions as SandBot's brain and focuses on high-level behavioral decision making. Commands from the central processor instruct the motor controllers to bring the legs to a desired position and speed. A position-tracking controller determines the discrepancy between a leg's actual state and the desired state. The controller then computes the voltage needed to correct the error and applies it to the motor using a class-D power amplifier. This action gets the leg into position at the right speed.

To economize on the robot's computational power, the computer issues commands at the comparatively lazy rate of about 100 times a second, which frees up its cycles for other tasks. The central processor might, for example, tell one of the microcontrollers that its leg should move at a particular speed starting from a certain position. From then on, all tracking of that leg's position is carried out by the microcontroller, which can interrogate its sensors at the much higher frequency of 1 kilohertz.

This design allows the central processor to communicate with the legs using extremely compact data packets that require minimal computing power to decode. The separation of the control tasks frees up the central processor to perform longer-range planning. The central processor might use a camera to assess the difference between its relationship to a visual landmark and what it ought to be



LEG ENVY: A zebra-tailed lizard and a ghost crab hold many secrets to fast running—such as how much a limb flexes on sand. The crab's backpack wirelessly sends measurements of the strain exerted by its legs.

or investigate how treacherous a surface is based on tactile feedback it retrieves from sensors in the legs.

SANDBOT'S DESIGN builds on experiments in Goldman's lab with real sand creatures. The zebra-tailed lizard, for example, can maintain a high speed over sand of almost any kind. The ghost crab, by contrast, is less versatile; on packed ground, its limbs and feet extend out from its 4-centimeter shell, and it scuttles along at a rapid 1 meter per second. But on looser soil the crab gets bogged down. The wind scorpion, for its part, can cover several body lengths per second even on granular slopes, where every step could trigger an avalanche.

Our observations of the lizard, crab, and scorpion under different conditions have helped shape our theory of sand locomotion. We believe this project represents the first attempt to combine direct measurements of a flowing physical substrate with observations of a runner's impact on the ground and its body movements. Broadly speaking, an animal's weight, foot shape, and gait all work together to apply a specific amount of stress to the sand. Under that model, the lizard is accessing the solid features of sand rather than slipping through the material and paddling, which is what the ghost crab ends up doing on softer terrain.

Much can be learned even from a single footstep. With each stride, the drag forces generated when a foot moves through sand can display both solid and fluid properties. If the stresses generated by the foot exceed a certain threshold, the material will flow. But it can also suddenly solidify if the stress drops sufficiently. That can happen, for example, if the downward forces produced by the limb and the weight of the robot are balanced by the amount of pressure within the sand, which is a function of its depth.

Another facet is that the behavior of sand depends on what's happened to it in the past. A section of solid sand disturbed by a footstep may be more loosely packed when the next foot hits the material, for example. The forces generated by a foot stepping into these different conditions can vary dramatically—the penetration resistance varies by a factor of 1.6 between a tightly packed material and a loosely packed one. That complicates the task of predicting how far a limb will penetrate in different granular states.

To learn how SandBot can best maneuver in sand, we have been subjecting it to a variety of precisely controlled granular environments. We control the environment using a 2.5-meter track built by Chen Li, a graduate student in Goldman's laboratory in Atlanta. The track looks sort of like a long bathtub, and it's filled with 90 kg of poppy seeds. There are tiny holes in the bottom through which we can blow air, causing the poppy seeds to lift off and dance before settling into a loosely packed state. (Why poppy seeds and not actual sand? We've found that each seed is large enough to keep us from worrying about it getting into the motors and yet light enough to be lofted by our air puffs. From separate experiments, we know that the exact material doesn't matter, as long as it is made up of granules.)

With sand and other granular media, we can describe the "strength" of the ground in terms of its solid volume fraction—that is, the fraction of the total volume occupied by the granules. Typically, the solid volume fraction falls between 58 and 64 percent for materials like sand or piles of seeds. A lower fraction means that, on average, there are fewer points of contact between the grains and that the material is less solid. In our test track, an exact sequence of hundreds of air pulses carefully packs the poppy seeds to the desired volume fraction.

Because RHex had been so successful at walking on a variety of surfaces, we assumed that the smaller but relatively more powerful SandBot would perform well on sand. We were wrong. In an early experiment, we packed the material to a solid volume fraction of 63 percent, placed SandBot on the surface, and set the frequency of the alternating tripod gait to 5 revolutions per second. Earlier, the robot had bounced flawlessly across hard ground using those same parameters.

This time, though, it got stuck after just a few steps. Like a car's tires spinning in mud, the robot's rapidly rotating legs produced absolutely no forward motion on the poppy-seed-filled track. Discouraged, our first assumption was that SandBot was simply too heavy to walk on sand and that we would need to completely redesign the robot.

But we decided to play around with it a bit more. Komsuoglu, conferring by phone from his office at Penn, suggested that we modify the gait slightly to make the legs swing faster in parts of the cycle and slower in others. He knew from previous studies he'd done that some robots perform better with such a varied gait, at least on hard surfaces. It seemed worth a shot. As Komsuoglu told us over the phone which values to change, we entered them into the control program and, like magic, the robot started to move! The robot was still cycling its legs five times per second, but now it was scurrying down the track at one body length per second. Further study showed that each limb penetrated the poppy seeds until it supported the robot's weight, providing enough stability for the machine to thrust up and forward.

With Paul Umbanhowar, a mechanical engineer at Northwestern University, we subsequently developed a kinematic model explaining the relationship between the volume fraction, the limb rotation frequency, and the depth of the limb's penetration at each step. As both the model and empirical evidence show, if we increase the frequency with which the robot rotates its limbs, the robot sinks further into the material and the size of each step decreases, triggering a catastrophic loss of speed—quite the opposite of what happens on hard ground.

ANOTHER IMPROVEMENT we're working on is building SandBot a better foot, to give it the ability to grip sand just as the zebra-tailed lizard does. To that end, we've been measuring the forces on the foot during impact with and penetration of materials of different volume fractions. The tests look deceptively simple: We embed accelerometers into simple disc-shaped objects and then drop them on piles of sand. The results show that the forces produced when a foot hits the ground have different qualities in high- and low-volume-fraction materials. When the sample foot falls into a low-volume-fraction material, the force on it increases until the object comes to rest. When the object falls into a closely packed material, the force decreases during penetration. To also investigate the drag and lift forces that arise during the other parts of each step, we use a robotic arm to maneuver model feet and toes along granular paths.

To fully model the behavior of individual granules, we must resort to simulation. Yang Ding, a graduate student of Goldman's, has developed a computer simulation that models collisions of objects with sand, beads, and other granular media. We hope that eventually these foot experiments and simulations will feed into the development of a new sensing and control system for SandBot, to enable it to sense the shifting terrain ahead and swiftly adjust its gait to match. Sand isn't the only morphing environment that the robot could eventually tackle: Mud and loose leaf litter also display the solid and fluidizing features of granular media.

Indeed, with physics models built into their feet and brains, robots should one day be able to scramble across a rocky or sandy environment and learn, on their own, how to handle the changes in terrain from footstep to footstep. We can imagine thousands of SandBots scouring the surface of another world, stepping from a pile of rubble to a sandy patch with ease. That's still a big challenge for today's machines, but it's something even a hatchling sea turtle can handle. Despite having appendages that are better suited for swimming, these remarkable animals must climb out of a deep hole in the ground, clamber over grass and debris, and move across sand to reach the water, where they will spend much of the rest of their lives.

We're also looking below ground for inspiration. Using high-speed X-rays, we are now studying lizards called sandfish that can burrow into sand in the blink of an eye and then "swim" through the material underground. We're hoping these creatures will provide clues as to how robots could scramble through an unpredictable disaster area after an earthquake or flood or dig down to detect land mines. With nature as our guide, we expect that robots will soon master some incredible new abilities. ❑

OUR OBSERVATIONS OF THE LIZARD, THE CRAB, AND THE SCORPION HAVE HELPED SHAPE OUR THEORY OF SAND LOCOMOTION

TO PROBE FURTHER
For more about SandBot and its robotic relatives, see http://www.spectrum.ieee.org/apr09/moresandbot.