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Why 6-Legged Bots Rule

Forget two-legged bots — forget androids altogether. Bio-guru Robert Full has seen the future of robotics, and it's one part cockroach, one part millipede, one part Internet.

By Tom McNichol

Dean Kamen has a problem. Sometime next year, the celebrated inventor aims to start selling his much-hyped Segway Human Transporter to the general public, and already the sharks are circling. Whereas Kamen views his self-balancing scooter as a device that will revolutionize personal transport and even change how urban landscapes are planned, personal injury lawyers take one look at the Segway, aka IT, and see lunch. One group of Washington, DC, attorneys emblazoned this phrase across their Sue-It.com Web site: "Get ready to Sue-It!" The Segway's primary weakness — inherent in any upright device with wheels — is lateral instability. Hit a nasty pothole at top speed (12.5 mph) and the Segway is likely to do what far less sophisticated scooters do — toss you off the side. In May, a member of Atlanta's auxiliary police fell off a Segway while going up a driveway; he was hospitalized with a knee injury.

So who does Kamen turn to for ideas on how to improve the Segway's design? A biologist. As a professor of integrative biology, and one of the world's foremost authorities on animal locomotion, 45-year-old Robert J. Full is the master of a quirky facility at UC Berkeley that analyzes the biomechanics and physiology of the sort of crawlie creatures most people would rather step on than study. In July, Kamen invited Full to Manchester, New Hampshire — home of his company, Deka, and the Segway. The idea was not so much to solve the scooter's stability problem as to stimulate new ways of thinking about it. Moving forward without falling over is a skill nature has been working on for a long time.

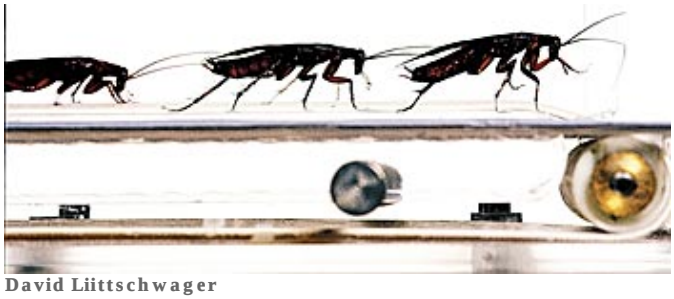
David Liittschwager
UC Berkeley biologist Robert Full has a unified theory of locomotion: All legs basically work the same way - though bipeds have disadvantages. Pictured: Full's size-10 feet, *Archispirostreptus gigas*, *Periplaneta americana*, and a Sprawlette robot developed at Stanford.

At Deka, it's easy to tell who's in charge. Large paintings of Kamen grace the walls of the complex, all rendered by Dean's father, Jack, who was an illustrator for EC Comics during the 1950s. The paintings are done in different styles and reflect the many faces of Dean: Day-Glo Dean, Lord of the Manor Dean, Shaggy Engineer Dean. Kamen is a man who knows his place in history, even before history has figured it out.

FULL'S ADVICE TO DEAN KAMEN: REDESIGN THE SEGWAY WITH SPRAWLED LEGS, NOT

WHEELS.

Not far from one of the largest paintings — a fluorescent Summer of Love Dean — Full is speaking to some 100 employees. Nearly all are wearing the same outfit as the Maximum Leader: denim work shirt, beat-up jeans, Timberlands. Full opens his presentation with what might be called a unified theory of legged locomotion. Having studied a diversity of animals, he and his colleagues have come to the surprising conclusion that no matter how many legs a creature has or how its legs are connected to its body — or what its skeleton is made of — all legs basically work the same way. Creatures don't progress smoothly as they run; rather, they alternately speed up and slow down, bouncing forward on springy legs like a pogo stick. "What happens when you poke these springy-legged animals?" Full asks the engineers. "How do they stabilize?"



David Liittschwager
Cockroaches posess speed and agility as their main solutions to the problem of mobility.

To answer this, Full shows the Deka engineers a video of an experiment that looks as if it came from the mind of a juvenile delinquent. He strapped a cylinder filled with gunpowder to the back of a cockroach, ignited the charge, and then stood back. The charge exploded with a bright flash, but when the smoke cleared, the cockroach was already scurrying forward, as if nothing had happened. "The amazing thing was, we found that the cockroach could correct for this perturbation in less than 10 milliseconds," he says. That's faster than any signal could possibly make it to the brain and back, which means the cockroach's movement isn't a reflex at all. Instead, it's what Full refers to as a "preflex." "The animals appear to be self-stabilizing; the legs are essentially doing computations on their own," he says. "In a sense, the control algorithms were embedded in the form of the animal itself."

THERE'S NO REASON WE CAN'T IMPROVE UPON NATURE. FIRST OBSERVE, THEN THINK SIDEWAYS.

At this point, one of the Deka engineers sitting close by lets out a soft "Whoa."

By the end of Full's presentation, more than a few engineers sit slack-jawed in their chairs. ("You could hear a pin drop," Kamen later recalls.) Full never mentioned the Segway in his presentation, but the implication is clear: The most stable scooter design would have sprawled legs, not wheels.

David Liittschwager
For geckos, the ability to stick to ceilings and walls is their distinct advantage.

When the lights come up, Kamen is perched atop a Segway, spinning distractedly in tight circles. He looks intrigued, and at the same time, a bit miffed.

A couple of weeks later, I call Kamen to see how he's processed Full's message. "Bob Full is a guy who has a very different perspective than a lot of the guys here. I knew that just about more than anyone in the world, people would appreciate listening to his thoughts on how nature very elegantly accomplishes moving around," Kamen says. Which is not to say he's ready to go back to the drawing board on the Segway — yet. "For a nice, smooth surface, I'm not sure I agree that legs are better than wheels. Bob looks at nature's response to moving in its natural habitat, and I'm coming out with man's response to living in a man-made habitat," Kamen explains. "Am I wedded to wheels? For now, of course. But the day you stop having an open mind, you're old."

A lot of people are picking Bob Full's brain these days. With a genial nature wrapped around a mind as quick as a lizard's tongue, Full is a widely respected for his biological insights. He's even more influential as a lateral thinker, adept at making connections across seemingly unrelated disciplines. His ability to blend hard science with a sense of fun has made him a favorite on the lecture circuit. For the last few years, he has been among the most popular speakers at TED, the

Technology, Entertainment, and Design conference in Monterey, California. Pixar hired him as a consultant for A Bug's Life, tapping Full's research to help animators express the various characters' personalities, and get them to interact realistically with their environment. Full's meticulous deconstruction of the way creatures, particularly arthropods, move and maintain stability is having a profound effect on a host of other fields, from engineering and industrial design, to animation and, especially, robotics. Because of Full's work at UC Berkeley's Poly-Pedal Laboratory (Pedal stands for Performance, Energetics, and Dynamics of Animal Locomotion), the robots of the future will probably move not like bipedal humanoids but more like crabs or cockroaches.

Contributing editor Tom McNichol (mcnichol@wiredmag.com) wrote about restoring the Nixon tapes in Wired 10.07.

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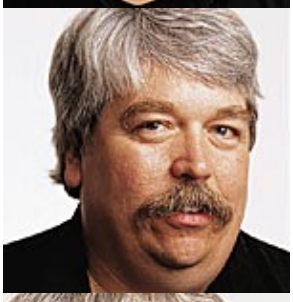
Full oversees a lab that's a sort of gymnasium for bugs and other varmints, containing some of the same equipment used to study human gait, only in miniature. A handful of SGI workstations running 3-D musculoskeletal modeling programs visualize motion data, analyzing animals in motion and breaking down their movements. The creatures are everywhere. Scorpions, with a highly stable gait that has evolved over 400 million years, scurry about. Cockroaches and centipedes are given a workout on tiny treadmills as a way to examine which muscles they use and how much energy they expend. Crabs scuttle across tiny scales that measure the various forces their legs generate. A gecko climbs smooth Plexiglas plates as high-speed video cameras, shooting at a rate of 1,000 frames per second, unlock the secrets of the reptile's amazing ability to crawl up almost any surface.

THE NETWORK, NOW EYES AND EARS TO THE WORLD, WILL SOON SPROUT HANDS AND FEET.



To the untrained eye, running bugs on tiny treadmills seems like the sort of project that could win a Golden Fleece award for being a ridiculous waste of taxpayer money. Not to mention that they're downright gross. "A lot of these creatures are really disgusting," Full admits. "But they provide surprising solutions to all sorts of problems. They're sort of a library of design ideas." Once nature's secrets of locomotion have been extracted, they can be applied to a wide range of engineering problems.

People often refer to this approach as biomimicry, but to Full that's a dirty word. Rather than slavishly aping nature, Full contends it's far better to extract her best elements and, where possible, blend them together. Think of a robot with the sprawled posture of a crab, the quick-moving legs of a cockroach, the complex coordination of a millipede, and a scorpion's ability to move in all directions, over rough terrain. As far as Full is concerned, there's no reason why we can't improve upon nature. All we need to do is look at nature with a discerning eye — and then think sideways. "Biomimicry is a really, really bad idea," he says. "Evolution isn't a perfecting principle; it works on the principle of 'just good enough.' If you really want to design something for a task, you have to look at the diversity of organisms out there and then get inspired by principles."

Full's approach to robotics was forged at SUNY Buffalo, where he received an undergraduate degree in biology and psychology, and, in 1984, a doctoral degree. He's won several teaching awards, and his classes are among the most popular at Berkeley. "No one forgets a class taught by Bob Full," says Kellar Autumn, who took a graduate course with Full in 1989. He's popular partly for his philosophy on science education and partly for his personality and style (Full has perhaps the world's largest wardrobe of black clothes, and he's the kind of guy who gets by on almost no sleep).

He has since become a champion of interdisciplinary science, working to get biologists, engineers, mathematicians, computer scientists, and physicists in conversation. Each expert brings a different perspective to the conversation, proposing a unique set of questions for the others to explore.

David Liittschwager
"A lot of these creatures are really disgusting," says Full, who demystifies movement at Berkeley's Poly-Pedal Lab. "But they provide surprising solutions to all sorts of problems."

Full's idea of an advanced robot goes far beyond anything available today. A lot of people think the best commercial machine these days is Asimo, the bipedal humanoid bot developed by Honda. Asimo features 15 joints with 26 degrees of freedom. It can step forward while changing directions and still remain stable, by predicting its next movement in real time and shifting its center of gravity accordingly. State-of-the-art, much of the robotics community agrees.

Dead end, counters Bob Full. "The Honda robot is extraordinary engineering, but there's nowhere to go from there," he says. Instead of trying to prescribe every joint angle and degree of freedom in a robot, a more efficient strategy, says Full, is to emulate nature's passive dynamic approach. Rather than making a robot's leg a dumb, passive receiver of commands, why not embed control algorithms in the limbs themselves, freeing up the central processor for higher-level operations?

Full's approach is already providing designs for a new generation of highly mobile legged robots. One of them goes by the name RHex, a hexapod developed by researchers at the University of Michigan and McGill University in Montreal. The bot's stance is a simplified version of the self-stabilizing sprawled posture found in a cockroach, with multiple legs splayed to the side, the body hanging low to the ground. RHex overcomes obstacles by rotating its legs in a windmill fashion, thanks to axlelike hip joints that turn full circle. The prototype has no external sensors because researchers want to see how much stability can be built into the design — as it is in nature. Even so, RHex is amazingly agile, able to scurry along at 9 feet per second; it can climb stairs, leap, and even swim. Now its creators have begun to layer sensors and more sophisticated capabilities onto the basic platform. RHex has caught the attention of defense experts at the Office of Homeland Security, who see its potential as a search-and-rescue bot. The machine's ability to negotiate the roughest terrain has made it a candidate to replace the six-wheeled Sojourner rover on a mission to Mars in 2012.

Full has also collaborated on Sprawl, a family of hand-sized hexapedal bouncing robots developed by Mark Cutkosky, professor of mechanical engineering at Stanford. Sprawl robots move at speeds of up to five body-lengths per second and can scale hip-high obstacles. The bots are constructed using a process known as shape deposition manufacturing, a kind of rapid prototyping process. Robot designs are worked out on a CAD system and then produced as a physical specimen in plastic. Cutkosky and his team build up multiple layers with different properties, embedding them along the way with components, sensors, actuators, muscles, circuits, and microprocessors. With this process, engineers can build robotic structures that have some of the complexity and robustness seen in nature.

"Nature has always been a source of ideas, but only now do we have the technology available to emulate nature in any detail," says Cutkosky. "Now can we make multimaterial structures that are like bone and tendons, or use micromachining to put a significant number of sensors in our robots. Ten years ago, we couldn't have built robots that embody the principles Bob Full has put forward."

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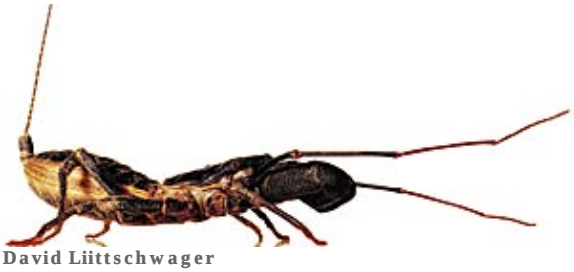
Not content to envision a world full of highly functional, supermobile robots, Full thinks bots will someday be networked. The Internet, now eyes and ears to the world, will soon sprout hands and feet. "You'll be able to run, swim, fly, do surgery — actually change the environment — remotely. Send a robot into your aging parents' home to monitor them, or have it clean up the house," Full says. "And all your devices will be more mobile, more programmable. You won't even notice them."



David Liittschwager
Self-stabilizing critters like the whip scorpion inspired the RHex robot (seen below).

Bob Full and bugs go back a long way. "I knew exactly what I wanted to do when I was 5 years old," he says. "I just didn't know how to get there."

Growing up in Buffalo, New York, Full's earliest memories are of the unusual creatures that he would later study in detail.

His family vacationed in Florida, where he became fascinated by the state's weird variety of crawling things: crabs, lizards, and a host of bugs. "Even then I was asking the question, Why are all of these animals built the way they are?" recalls Full. "I was just fascinated by crabs and how they moved."

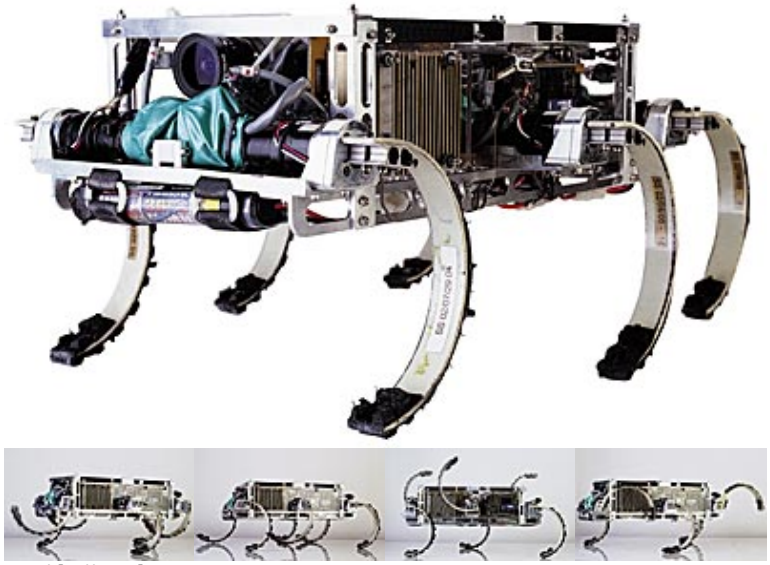
A current fascination: the gecko, perhaps best known for its uncanny ability to climb smooth surfaces and stick to ceilings without the aid of claws. Astounded by this ability, Full first shot a high-speed video of a gecko ascending a vertical plate in 1998. Then he compared it to video of a gecko moving horizontally. The result floored him. The gecko running up the wall is indistinguishable from the one advancing along the floor.

"We were just blown away by this," says Full, hand pressed to forehead. "They can attach their toes to a surface in 8 milliseconds and detach them in 16 milliseconds. And they perfectly match their grip with the speed they're going. We couldn't figure out how they did it."

Using an electron scanning microscope that magnifies images 100,000 times, Full examined the toes of a tokay gecko, which is native to Southeast Asia. Gecko feet have about half a million tiny hairs, or setae, on each toe. The end of each seta has billions of nano-size split ends called spatulae, which come in direct contact when a gecko toe attaches to a surface. But how do they manage to stick so firmly and detach so easily? "People have been studying how geckos climb smooth surfaces for the last hundred years, but no one really understood how they did it," Full says.

Full and a team of PhD students tested numerous hypotheses. They looked into friction, electrostatic charge, interlocking forces, suction, and wet adhesion. No luck. Then Full came up with a solution straight out of his high school chemistry textbook. The way geckos attach to surfaces, he now believes, is through van der Waals forces, which every 10th-grade chemistry student learns are the weak attractions that molecules have for one another when they are brought very close together. In fact, van der Waals forces are so weak that no one would think of them as having adhesive properties. But when billions of gecko spatulae come in close contact with a surface, the cumulative interaction between molecules in the toe hairs and the molecules on the surface create a very strong bond. When a gecko foot is fully attached, it can support the weight of a 40-pound child.

And by simply levering the hair upward at a 30-degree angle, the spatulae easily detach.



David Liittschwager
The low-slung RHex can leap, swim, and climb stairs. The highly mobile robot has drawn the interest of NASA and the Office of Homeland Security, for use in space and search-and-rescue missions.

Full thinks that by unlocking the gecko's secret he may have discovered the biological inspiration for a remarkably effective, self-cleaning dry adhesive, "sort of one-sided Velcro," as he puts it. Unlike today's adhesives, it would feature more smarts than stickiness, attaching and detaching with a minimum of pressure. Full and his colleagues have a patent pending, and UC Berkeley engineer Ron Fearing is working to fabricate synthetic gecko setae, which could be ready as an adhesive in a year or two.

The potential uses are amazingly varied. Johnson & Johnson is interested in the dry adhesive for improved ouchless bandages. Semiconductor companies could use it to move chips in a clean room without scratching them. NASA could make "gecko tape" that would work in the vacuum of space. DuPont and 3M have expressed interest in it as a next-generation adhesive that sticks anywhere, detaches easily, and doesn't get dirty. Even Nike has approached Full to riff on reptile-inspired climbing shoes.

Air Gecko?

"I could make a lot more money than I am now with this," Full admits. "I talked with my wife and two daughters about leaving teaching and setting up a company. But we decided that's not what I do best. I'm happy with what I'm doing."

The crowds that come to hear Bob Full speak are as diverse as the creatures he studies, and sometimes as hard to control. A few days after talking to some of the country's top engineers at Deka, Full finds himself addressing a classroom of rambunctious grade school kids at the New York Hall of Science, in Queens. Kids light up when Full addresses them, probably because they see him as one of their own at heart. (It doesn't hurt that he has a distinct Captain Kangaroo quality about him.)

"There's a lot of fun stuff that professors do, like study bugs, that I liked to do when I was your age," Full tells the kids, while a video of a millipede undulating on one of his treadmills plays behind him. "Unfortunately, they often don't tell you that in school. I don't know why."

A little girl in a pink flowered dress suddenly pipes up, "I have a millipede at home!"

"I study millipedes!" Full says excitedly. "Aren't they cool? We're still not sure why they have all of those legs."

The little girl beams. For Full, science is still about the thrill of discovery, about being the first human to answer a question about nature and then passing along the answer — and the excitement — to others. If not enough kids are attracted to science these days, it's partly because adults have drained the fun out of it. Scientific discovery, at its root, springs from a sense of wonder, a wellnurtured capacity to be amazed.

"The greatest discoveries are the ones you can't anticipate," says Full. "That's why funding curiosity-based research is so important. Give money to people who are curious to try new things

and you'll get great stuff.''

Full's own work is proof that curiosity — and a nimble mind — can lead in unexpected directions. Which is not to say that being recognized as one of the country's foremost bug experts doesn't have its drawbacks. Full receives dozens of emails from strangers wondering how to get rid of the cockroaches scuttling around their houses.

"I have to tell them that I don't know anything about killing bugs," Full says, smiling.

"I just run them on treadmills."

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