WORKING OUT THE BUGS

Programming a robot to think like an insect is tough, finds **Alison Abbott**, but it could help breed machines as manoeuvrable as flies.

Tarry II looks like a robot, sounds like a robot, and walks like an insect. He sprouts a tangle of wires, and the mechanical joints on his six legs emit a metallic creak with every step. But he strides determinedly across the lab with the steady gait of a fly marching towards rotting fruit.

The strutting machine is the work of Roland Strauss at the University of Würzburg and robotics colleagues elsewhere in Germany. Strauss acquired a zeal for mechanics as a schoolboy, when he won a national prize for designing electronics that could imitate a crab's visual system. But his real passion was always biology, and his goal today is to understand how behaviour involving movement is controlled in insects. He has recruited Tarry II and a small army of other biorobots to help.

Although our encounters with flies often leave an impression of aimless and irritating meandering, these tiny creatures' decisions are just as purposeful as those of other animals. A fly scans its environment with eyes and antennae, processes this information in its brain and then makes a decision, perhaps to turn away from potential danger or hurry towards food. Strauss aims to tease apart the complex of brain circuits that coordinates such movements. He hopes to identify broad principles about how the brain directs these behaviours, which might also apply to other animals including, perhaps, ourselves.

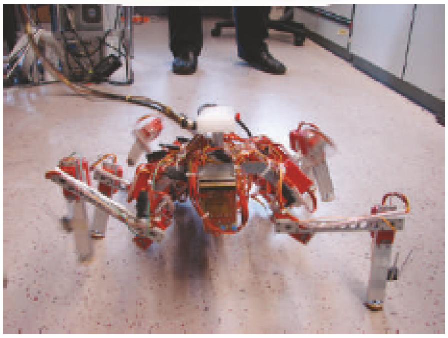
To help, Strauss and a handful of other insect biologists have turned to robotics experts. By programming simple robots to react to stimuli and move in particular ways, they can test biological hypotheses about which neural networks an insect uses to navigate.

And the biologists hope to return the favour. The algorithms they use to direct their biorobots could in the future help design smarter and more agile robots, capable of overcoming many barriers without direction from humans. (Videos of both insect-like robots and insects whose movement behaviour has been experimentally manipulated can be seen in this feature on the *Nature* website.)

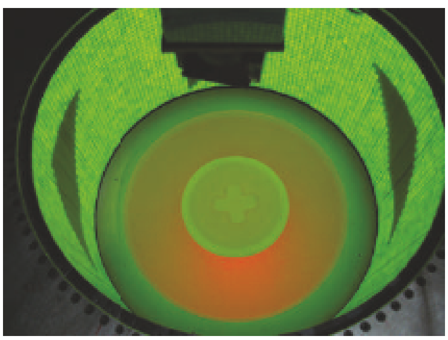
If only the Mars rovers had been more like cockroaches, sigh insect biologists, they might have been able to extricate themselves from the sand dunes and rocks on which they have occasionally come a cropper and had to be carefully steered to safety by their human controllers. "We are very happy if what we learn from nature can be put to use to make better robots," Strauss says.

A large amount of insect movement occurs without guidance from the brain. It is instead directed by circuits of nerves in the nerve cord, which extends from the insect's head into its thorax and is equivalent to the vertebrate spinal cord. If you decapitate a fly it will stop moving because the brain no longer provides the 'go' signal. But if you drop a neurotransmitter such as octopamine directly onto its thoracic nerve cord, then it will start to walk around like — well, like a headless chicken[1]. The fly can even be induced to carry out more complex and ghoulish behaviours, such as grooming eyes that are no longer there. These basic movement programmes are well studied and have been transferred to robots. Tarry II's prototype, designed by biorobotics pioneer Holk Cruse at the University of Bielefeld, has been walking with the confident coordination of a decapitated stick insect for more than a decade (see video 1 on *Nature*'s website).

R. STRAUSS



A. ABBOTT



R. STRAUSS

Insect-mimics Dro-o-boT (top) and Tarry II (middle), and a chamber for studying fly movement (bottom).

Executive decision

But for the cleverer stuff — deciding when to move, at what speed and in which direction — the insect recruits its brain. Just as we do. And just as robots should, but cannot, because current algorithms do not to provide them with this level of sophisticated and autonomous decision making.

Like other animals, an insect's brain contains specialized circuits responsible for controlling particular aspects of behaviour, spanning defined anatomical areas. So biologists have begun to decipher which particular region is involved in directing each type of movement by destroying that area and watching what happens. Strauss likes to work with the fruitfly *Drosophila melanogaster* because genetic tools are available to selectively damage very specific brain areas. Researchers can, for example, introduce random mutations into the fly's genome and then screen for flies that walk or move abnormally. In many of these, a mutation will have interfered with the structure of a particular brain region.

Using such methods, Strauss has accumulated a collection of several hundred mutants with aberrant movement behaviours. A large proportion have damage to a brain structure called the central complex, a collection of components sitting between the two hemispheres of an insect's brain known to be critical for

DK LIMITED/CORBIS

virtual-reality environment. Dro-o-boT has an integrated 360° camera for eyes and was programmed to integrate visual information on the size of 'objects' with its own movements, so that it could recognize and wheel itself towards the dark spot that appeared closest (see video 2). Movement traces of Dro-o-boT confronted with four landmarks were virtually identical to those of a fly confronted with an equivalent four landmarks, showing that parallax motion is indeed sufficient to direct this type of movement.

In the past couple of years, Strauss's group has similarly programmed Tarry II so that it can imitate flies even more closely than the wheeled Dro-o-boT, by using parallax motion to identify and approach the closest object on its six legs. The robot can even follow the movements of its owner relative to marks on the more distant wall and change direction to move towards him (see video 3).

Having explored how a fly reacts to an object, Strauss is now starting to examine other movement behaviours, including walking speed. Such is the simplicity of a fly's brain that if two black squares appear directly opposite each other on the cylinder walls, it will walk towards one, then turn at the moat and pace back towards the other, lacking the intellectual wherewithal to choose a destination. It thus continues a seemingly pointless march until fatigue sets in (see video 4). This is known as the Buridan paradigm, after 'Buridan's ass', a thought experiment in which a donkey placed exactly between two identical piles of hay is destined to starve to death because it cannot decide which pile to choose. In another variation, the virtual-reality environment is set up with vertical lines and rotated, making the insect circle at the same speed as it continually tries to walk towards the nearest object.

The fly's predictable behaviour in these paradigms is useful for experimentalists because it allows them to find mutants with brain damage that interferes with their turning, walking speed and resoluteness (the time before

executive control of movement. Mutants with a damaged central complex might walk more slowly, or spiral their way towards an object of desire instead of approaching it in a straight line. Over the past ten years, Strauss has dissected out exactly how different regions of this complex cause specific movement or orientation problems, and he is now starting to see if he can translate these functions successfully into algorithms for Tarry II as well as for a newer, wheeled machine called Dro-o-boT.

Already these robots have supported his hypothesis that flies use parallax motion to gauge distances — the motion familiar to train passengers, who see close objects rushing past while distant ones seem to move slowly. The ability to gauge distance is critical for flies; they approach stationary objects in the hope that they may turn out to be safe havens or sources of food, and to save energy they always approach the closest first.

To monitor how flies move when they see objects, Strauss built a virtual-reality environment which looks like a a nightclub for flies. The setup consists of a small cylinder with a glass floor, and walls packed with light-emitting diodes that can be programmed to create geometric patterns of light and dark. The movements of a fly placed in the centre of the floor are videoed from above, and each footfall is recorded automatically from below. Test flies have their wings clipped so they cannot fly, and a tiny moat keeps them in the central arena because they are repelled by water.

Parallax view

Flies, it turns out, will move towards dark shapes created by unlit diodes as if they were real objects. To test his parallax-motion hypothesis, Strauss programmed his virtual-reality environment to automatically move the shapes according to the flies' movements. The flies did, as predicted, use parallax motion to identify the nearest 'object', which they approached[2]. But Strauss next wanted to test whether insects use parallax motion alone to judge distance or whether they also recognize what the objects actually are. For this, he turned to Dro-o-boT.

The researchers placed Dro-o-boT in a scaled-up, two-metre-square model of the

"Robots are going to help us work out increasingly complex movement behaviours in insects."
— Robert Full

they simply give up the march). Many of the mutants that performed badly in these two experiments turned out to have damage to a structure within the central complex called the protocerebral bridge, a string of nerves which Strauss has shown changes the swing speed of the leg and hence controls step length. In one of his mutants, appropriately called 'no bridge', the bridge is cut right through. Another, called 'tay bridge', after a Scottish bridge that collapsed disastrously in 1879, has a decided kink.

Normal flies take longer strides when their stride rate increases, to gather speed efficiently. But in Buridan's paradigm, tay bridge mutants did not increase stride length, walked at half the speed of normal flies, and gave up earlier. In the rotation paradigm, neither the no bridge nor the tay bridge mutants could keep up with the moving stripes.

Mind the gap

Strauss used Tarry II to understand in more detail why these mutant flies are so sluggish. Graduate student Simon Pick, now at the University of Ulm, Germany, programmed Tarry II to mimic the mutants so that the robot no longer increased stride length with stepping frequency. In doing so, he uncovered what robotics experts call an emergent property. He found the tay bridge way of walking was not just slow, but also inefficient — it consumed 8% more energy for a given speed than normal walking. "We didn't expect it, but the robot simulation made us realize that energy efficiency is an important evolutionary advantage for walking insects," says Strauss. The evolutionarily ancient brain of the stick insect, he notes, is not so sophisticated: the insect can vary only step frequency, not step size.

Strauss is now turning his attention to more complex movements: his current preoccupation is how flies climb across gaps. By filming flies as they confront gaps of varying widths, he has described distinct units of behaviour as the flies try first of all to assess the width of the gap, then initiate and complete the crossing or, alternatively, topple into the abyss.

When a fly stumbles upon a chasm, for example, it typically raises its front legs high above its head and performs far-reaching climbing movements as if it were feeling for a way across. If it fails to find a way over, a normal fly tries again and will eventually throw its body across to grasp the far edge. But Strauss has identified several mutant lines which consistently foul-up gap-crossing, and seem unable to improve. One fails to reach the other side correctly because it initiates leg-over-head movements too early. Another fails to even start the crossing, choosing instead to turn tail and walk away[3] (see video 5).

Strauss wants to use his robots to test how flies control their reaching when they negotiate gaps — but these complicated behaviours are difficult to model in machines. He is planning to fit Tarry II with attachments that would allow him to climb in the same way as flies need to when they cross a gap. "One might think about Velcro attachments and an environment with carpeted walls, or claw attachments with Styrofoam walls," he says.

Mutant fruitflies are a treasure trove for movement-behaviour researchers, but their minuscule brains do impose some experimental limitations. The cockroach brain, on the other hand, is 50 times larger, so researchers can inflict brain damage using surgery. Other advantages are a matter of taste. "Cockroaches can actually be quite pretty, I think," says neuroscientist Roy Ritzmann from Case Western Reserve University in Cleveland, Ohio, "and my sort [*Blaberus discoidalis*] don't really smell so bad."

About turn

In one series of experiments, Ritzmann removed the cockroaches' wings and severed the circumoesophageal connective, the part of the nervous system that separates the lower and upper parts of the brain. Following this procedure, cockroaches will walk until they drop, but cannot negotiate obstructions. When climbing an incline of 40–45°, for example, their legs might slip and they sometimes fall backwards in slapstick fashion (see video 6). This is because some of the brain-damaged insects are unable to control the height of their bodies and tend to raise their centre of mass too high, so adhesive pads on their legs no longer stick[4].

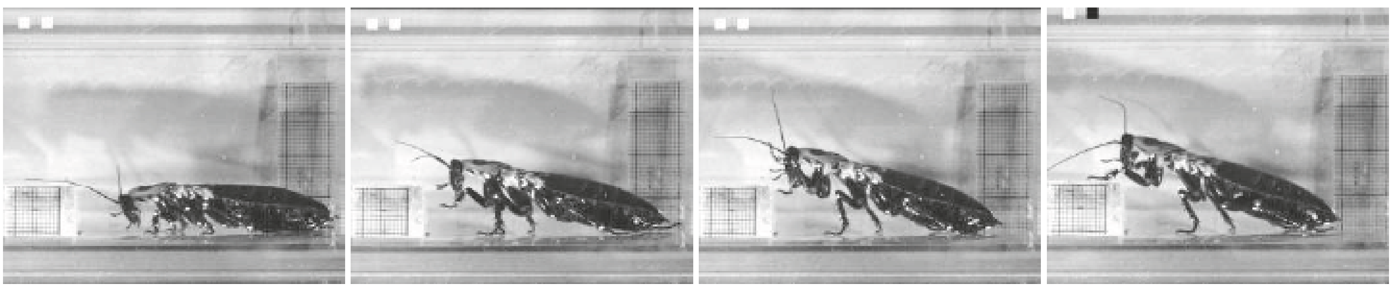
Like Strauss, Ritzmann wants to unravel the neural mechanisms his creepy-crawlies use when confronted with obstacles, behav-

Why robots need legs

Just as horses use different leg sequences when they trot, canter or gallop, six-legged insects have different gaits depending on their speed. On a smooth horizontal surface, a fruitfly normally adopts an alternating tripod gait, where the front and back leg on one side, and the middle leg on the opposite side, swing together in unison supported and balanced by the other three legs in a sturdy tripod. To move faster, it will increase both the frequency of steps and the speed of the swing to lengthen the stride. To turn, it reduces the length of the stride on the inside of the turning curve.

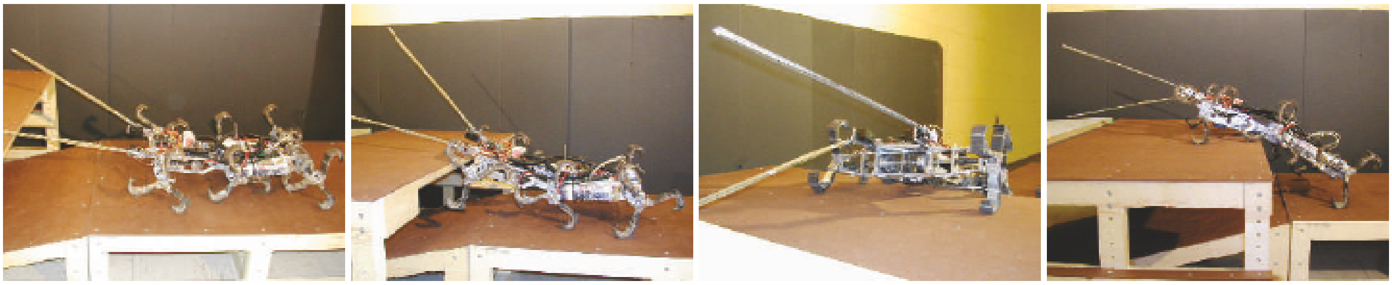
When a six-legged insect walks slowly, it adopts a tetrapod gait, where legs swing together in a type of wave from front to back and at least four legs are on the ground at the same time. Both gaits can stably accommodate objects underfoot — the insect simply adjusts its body position for balance.

Evolution has found different ways to achieve balance and locomotion in insects and vertebrates — and now robot designers must solve the same problem. Legged robots, with their stability and flexibility over uneven ground, offer clear advantages and some machines already copy their style. By using the tripod gait, for example, the Finnish Forest Walking Machine is unfazed by rough terrain that might defeat vehicles with caterpillar tracks. And the US Department of Defense report following the terrorist attacks on the World Trade Center commented that legged robots might have been better at locating bodies in the rubble. **A.A.**



R.E. RITZMANN

Up and over: a cockroach will climb over a shelf if its antennae touch the top of it first, behaviour that robots can mimic (see opposite page).



R. QUINN

The roach approach: a Whegs robot, moving on a cross between wheels and legs, clambers over a shelf using rules copied from cockroaches.

iour which is coordinated by the central body complex. His students carefully exposed the brains of cockroaches and used tin foil to make cuts through the complex. They then identified ones that no longer turned correctly by videoing them in a transparent chamber and later dissected out the brains to identify exactly which part had been damaged.

Intact cockroaches turn to the left when their right antenna touches the wall, and vice versa. But few of Ritzmann's lesioned cockroaches could turn properly. Depending on where the cut was made, some animals could turn only in one direction, some circled continuously and others were disinclined to turn at all, crashing into the walls[5] (see video 7).

These disabled roaches have helped Ritzmann develop a hypothesis that the insect brain goes through three distinct mental steps when it confronts an obstacle: it must detect the block, decide that it would be appropriate to turn, and then decide which way to turn. Ritzmann now wants to test this hypothesis by programming these three steps into a robot; he is collaborating with colleague Roger Quinn in the university's biorobotics laboratory. Quinn's six-legged Robot III is modelled on the *Blaberus* cockroach and it already possesses the astonishing stability of a headless insect — give it a strong shove, and it will find its feet again almost instantly (see video 8). But this work is just beginning and as yet Robot III can't walk very well, let alone negotiate turns.

Using a particularly manoeuvrable breed of robots called Whegs, Quinn has tested another of Ritzmann's hypotheses about a behaviour at which cockroaches seem adroit — climbing over or slipping under a shelf.

On the shelf

Whegs, so called because they are propelled by a cross between wheels and legs, have the tripod gait of all six-legged insects (see 'Why robots need legs') and can flex their bodies thanks to a special body joint. Quinn used his robots to test the idea that a cockroach's decision to clamber over or crawl under the shelf depends on whether its antenna first brushes the shelf's top or its underside. This is hard to prove definitively in the insects because many types of information or neural circuits might be involved in the decision. But a robot, which can be programmed with a set of algorithms so that it reacts only to information from the antenna, can reveal whether this sensory input is sufficient to direct its behaviour. Quinn's student William Lewinger added suitably programmed antennae to the Whegs, allowing the robot to detect a shelf's top or bottom and trigger it to climb or crouch respectively. As predicted, the robot behaved just like the real roach (see video 9).

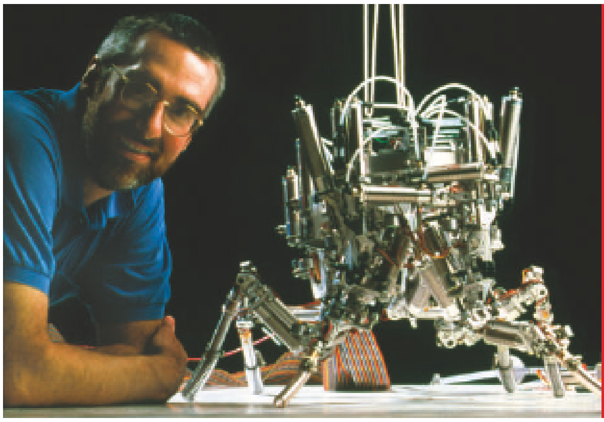
Insect biologists are eager to model ever more intricate types of insect behaviour in their robots, such as walking uphill or climbing, and some robots with this hardware capability already skulk in other labs. One six-legged machine called RiSE, built by a team at Carnegie Mellon University, Pittsburgh, can even climb trees. "Robots like these are going to help us work out increasingly complex movement behaviours in insects," says Robert Full at the University of California, Berkeley, whose studies on the mechanics of insects and other arthropods have inspired RiSE and other machines. But until these robots can be programmed with more sophisticated and autonomous software — precisely the directions that biologists are extracting from insect's brains — they cannot pass for true robotic insects (see video 10).

Insect biologists aren't the only ones anxious to tap into flies' intellect. Just a few of an insect's effortless navigational skills would be a boon for many of today's applied robots, which can negotiate obstacles only via human intervention and remote control. For this reason, space agencies such as NASA and the European Space Agency are watching developments in these insect labs with keen interest — and many robotics groups already include neurobiologists on their teams. "We think we may find it easier to go to higher control levels with neurobiological input," says Dirk Spenneberg of the University of Bremen, Germany, who works on autonomous robots including six- and eight-legged machines.

Quinn, for example, says he is working with NASA to determine whether Whegs could work well on the lunar surface, and has other collaborations exploring their use for surveillance, and search and rescue. And nothing would make insect biologists happier than seeing future generations of Tarry lookalikes confidently striding the canyons of Mars. ■

Alison Abbott is *Nature*'s senior European correspondent.

P. MENZEL/SPL



"Roger Quinn says he is working with NASA to design robots that can work on the lunar surface, and has other collaborations exploring their use for surveillance, and search and rescue."

1. Yellman, C., Tao, H., He, B. & Hirsh, J. *Proc. Natl Acad. Sci. USA* 94, 4131–4136 (1997).
2. Schuster, S., Strauss, R. & Götz, K. G. *Curr. Biol.* 12, 1591–1594 (2002).
3. Pick, S. & Strauss, R. *Curr. Biol.* 15, 1473–1478 (2005).
4. Ritzmann, R. E., Pollack, A. J., Archinal, J., Ridgel, A. L. & Quinn, R. D. *J. Comp. Physiol. A* 191, 253–264 (2005).
5. Ridgel, A., Alexander, B. E. & Ritzmann, R. E. *J. Comp. Physiol. A* doi:10.1007/s00359-006-0193-7 (2006).