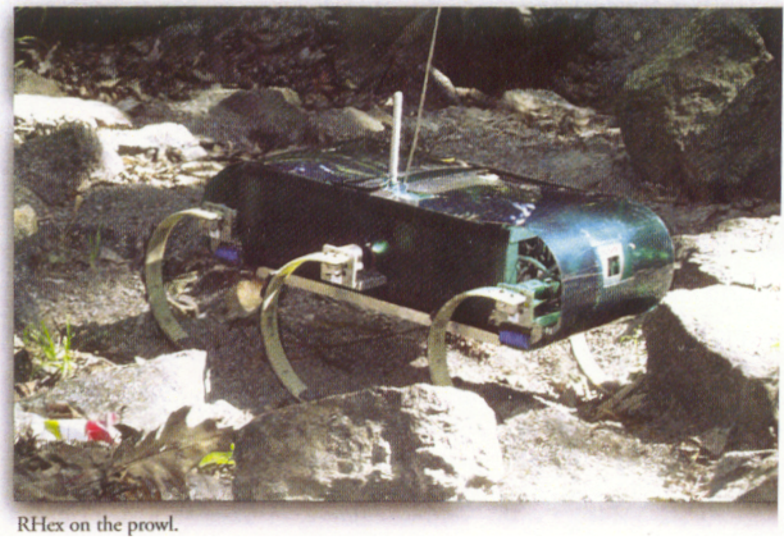
Robots Take a Cue from

BIOMIMETIC SENSING AND CONTROL ENHANCE MOBILITY AND AUTONOMY IN LAND, AIR, AND SEA ROBOTS



RHex on the prowl.

by Geoffrey L. Barrows

Recent discoveries in animal locomotion and sensing are enabling the development of better-moving robots able to autonomously operate in complex environments.

The Defense Advanced Research Project Agency (DARPA) Controlled Biological and Biomimetic Systems (CBBS) program, managed by Dr. Alan Rudolph, is funding a number of research efforts that study animal locomotion and navigation to gain insights that can be applied to make new classes of ground, airborne, and underwater robots.

Some of the projects are studying walking animals, which have evolved gait patterns and localized control rules allowing rough terrain to be easily crossed. Other projects are studying flying insects, which have evolved sensing organs and simple but robust flight behaviors that enable them to travel without bumping into obstacles. Yet other efforts focus on how underwater creatures swim. Also underway is engineering work on actual "biomimetic" robots with enhanced locomotion and navigation capabilities.

Conventional terrestrial robots make use of wheels or tracks to move. This is effective for traveling on roads and smooth surfaces, but less effective on rougher "off road" terrain. Legs are more appropriate for such environments because of their ability to step over objects. The technical challenge is coordinating the motions of multiple legs to form gaits that yield fast, energy efficient transfer of weight for motion. The DARPA CBBS effort has produced two walking robot platforms, the six-legged "RHex" and the eight-legged "Scorpion," that move around using animal-inspired gait patterns.

A team led by University of Michigan Professor Daniel Koditschek has developed "RHex," a six-legged robot whose design and controls are inspired by locomotion strategies of the common cockroach. RHex presently holds the record for untethered legged machine speed and endurance. This was achieved by employing different gaits for different operations over widely varying terrain types — running over hard level ground at speeds greater than one body length per second, scrambling over obstacles well exceeding its ground clearance, leaning into steep slopes, turning, and so on.

Professor Robert Full, a UC Berkeley biologist working with the team, has led numerous studies demonstrating that animals run as if their mass centers are riding on a "pogo stick." When a leg steps onto a surface, the body's mechanical energy is stored in the spring, then restored to power the body's progress as the leg lifts off. This mechanism enhances agility and reduces the energy lost in ground contact, resulting in more efficient locomotion. Gaits that entail multiple legs hitting the ground at once can be analytically treated as a single "virtual" leg, which simplifies the analysis while yielding the same insight.

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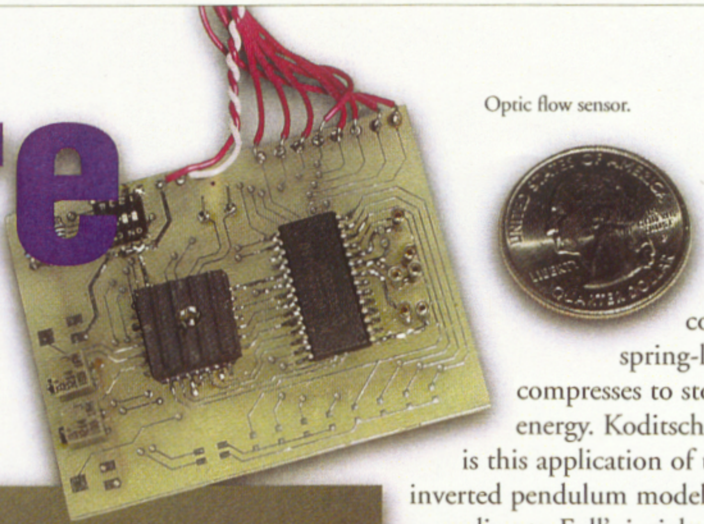
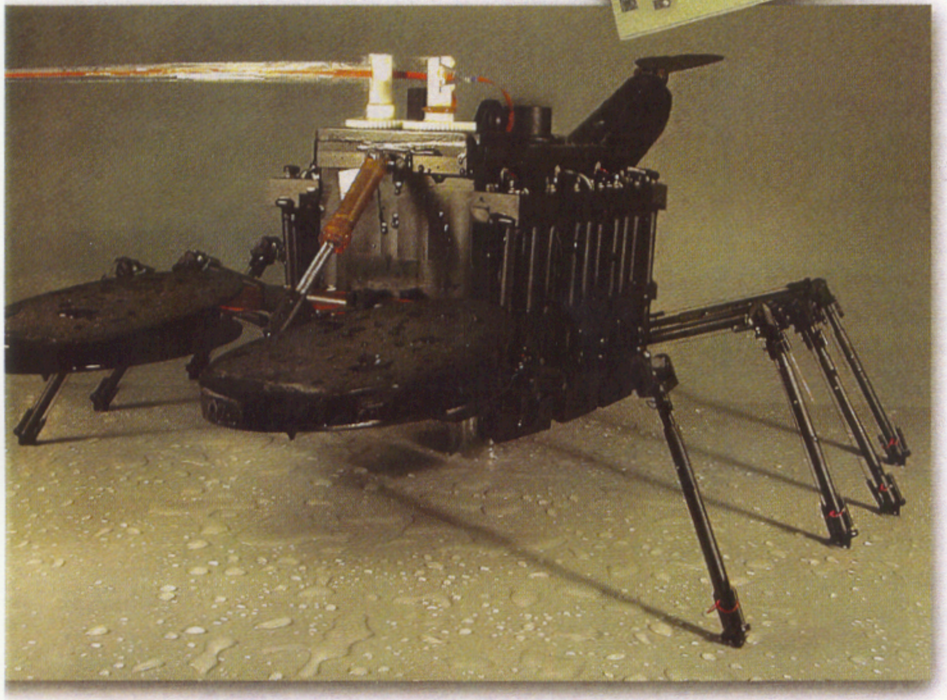


Optic flow sensor.



Anyone for lobster?

Thus the pogo stick model can be used to understand and optimize the performance of any practical gait used by a walking robot. The sprawled posture and specific patterns for controlling RHex's legs are inspired from locomotion studies of cockroaches in the laboratory. As the cockroaches are directed to run over different obstacle courses, cameras capture the leg motions while special ground plate scales measure the force produced by each leg during the gait cycle.

The specifics of RHex's body, actuator and leg designs, and the accompanying internal "central pattern generator" (CPG) that governs RHex's rhythmic leg motions were developed by McGill University Professor Martin Buehler, who combined biological inspiration with a mechanically and electronically minimalist approach to insure reliability, robustness and energy efficiency adequate for extended outdoor operation powered only by two small onboard batteries. Buehler's leg designs, being mechanically one piece, do not have a true joint, but incorporate a tuned mechanical compliance — a spring-like quality that compresses to store and release energy. Koditschek believes that it is this application of the spring loaded inverted pendulum model, interpreted according to Full's insights into the specific virtues of cockroach morphology by Buehler's careful engineering design that affords RHex its unparalleled mobility.

A different platform, the Scorpion, is the work of Dr. Frank Kirchner of German National Research Center for Information Technology. The Scorpion has six or eight legs, with each leg having three degrees of freedom. The increased degrees of freedom available enable the legs to generate a wider variety of motions. Just like RHex, a "central pattern generator" controls the leg motions. Each leg is controlled by its own virtual controller that directs the leg motion and reacts to a pressure sensor mounted on the foot. The pressure sensor detects contact between the leg and the surface. Each leg's virtual controller connects with the virtual controllers of adjacent legs.

The array of virtual controllers interact to form task depend clock pulses that modulate the motions of individual legs. The CPG allows the leg position and drive forces to be adapted to variations in the ground terrain. The legs up front can effectively send "suggestions" to legs in the rear to optimize foot placement for efficiency. These virtual controllers are currently implemented as individual subroutines within a central computer. However in a future system they could be implemented each in a separate microcontroller, with each controller hooked up to the others to enable the appropriate interactions between legs. The Scorpion is currently able to walk over a variety of surfaces, including over obstacles taller than its body. Kirchner believes that with additional improvements, the Scorpion will be able to climb up rough and steep surfaces.

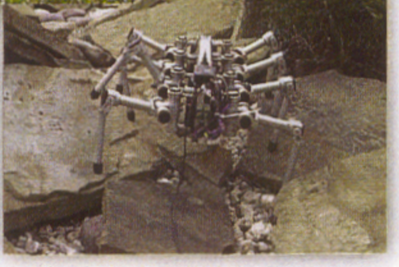
On the other hand, aquatic animals have long served as models for neurobiological studies of the mechanisms of locomotion. Unlike terrestrial animals that must exert

Insects provide insight.

considerable force to counter gravity, marine animals are only slightly negatively buoyant and spend more energy overcoming flow and surge. Since such fluids touch the animal body all over, the animal is able to change its body shape to generate propulsion. Animals such a fish and lamprey generate undulations in their body to generate propulsion. Shellfish with claws, such as lobsters, additionally use their claws as control surfaces to provide mobility in shallow water regions, which have heavy turbulence.

Professor Joseph Ayers, a neurobiologist at the Marine Science Center of Northeastern University, and another DARPA CBBS participant, has adapted a neuronal network-based central pattern generator and muscle controller for use in underwater robots based on the lobster and lamprey. These robots also incorporate control surfaces such as claws and fins that are modeled after those of the real marine creature. The neuronal network generates trains of current pulses used to control a muscle made of nitinol, a metal that changes length when heated. These robots use animal like sensors such as antennae to mediate adaptive reflexes to collisions and flow based on studies of the corresponding reflexes observed in the animal models. This biomimetic architecture allows the investigators to incorporate into the robots different action patterns exhibited by ocean animals.

Meanwhile, Mini- or Micro-air vehicles (MAVs), a new class of UAVs with a small size (<1 meter wingspan), can benefit from research on the sense organs and flight behaviors of flying insects. Proposed MAV applications include flying low to the ground and even among obstacles, which requires navigation based on sensing other than the Global Positioning System (GPS) for altitude control and collision avoidance. To provide such capability in a package that is light enough to fit on a MAV requires radical adjustments in sensing and flight control. The world of insects, which has evolved lightweight yet robust sensor and control systems, is a natural source of inspiration.



Stingless Scorpion.

Insects make heavy use of visual cues for navigation. Many important visual cues are provided by "optic flow," which is the apparent movement of texture in the visual field resulting from the insect's motion. Optic flow can be used for depth perception. For example, a flying insect can estimate its flight altitude from the perceived optic flow in the downward direction, which increases as the insect flies lower. An insect can also perceive obstacles in the forward direction by detecting expansion, or divergence, in the forward direction. The "focus of expansion" (FOE), from which the optic flow originates, indicates the direction of heading. If the FOE is located inside a rapidly expanding region, then a collision is imminent.

Professor Mandyam Srinivasan, of the Australian National University (ANU) has extensively studied how honeybees use optic flow cues to perceive their environment and avoid collisions with obstacles. Srinivasan has observed a number of "stratagems," or heuristics, that the insects use in flight. For example, honeybees will fly down the center of a tunnel by equalizing the optic flow on left and right sides. There is also evidence that honeybees estimate distance traveled by integrating over time the optic flow in the sideways directions. Furthermore, honeybees can execute a "perfect" landing by keeping the downward optic flow constant while continuing to approach the ground at a fixed angle.

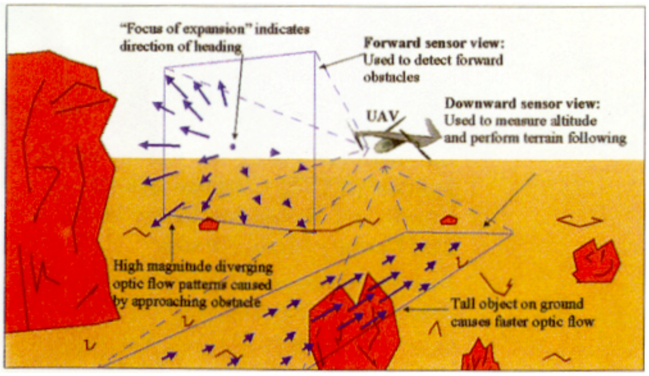
Another important visual sensor is the occelli system, comprised of tiny eyes located on top of an insect's head near the larger compound eyes. These occelli have very low resolution, and are believed to respond primarily to the horizon for flight stabilization. The horizon is located by detecting differences in light intensity, spectra, and polarization between, above, and below the horizon. Professor Javaan Chahl, also of ANU, has implemented a horizon detector with artificial occelli modeled after those of the dragonfly.

Srinivasan and Chahl are leading an effort to insert biologically-inspired sensors and flight control stratagems onto both rotary- and fixed-wing aircraft. Using an optic flow sensor aimed downward and an off-the-shelf gyroscope, this group has demonstrated autonomous altitude control on a small (2m) helicopter. Furthermore, using an optical stabilization device modeled on the dragonfly occelli, this group has demonstrated autonomous terrain following on a small (2m wingspan) aircraft. The artificial occelli detected the horizon to assist with perceiving changes in terrain and stabilizing the aircraft. This group is currently working on autonomous collision avoidance with the use of both optic flow and horizon detection in the forward direction. These technologies are flying today and could go soon go into tactical mini-UAVs.

Ultimately these sensing capabilities will need to be extended to tinier aircraft having a 15-20cm wingspan and a payload capacity of less than ten grams. A significant challenge is that of fabricating an optic flow sensor that fits such a weight budget.

With support from both the Naval Research Laboratory and DARPA, the author, founder of Centeye, Inc., has developed a class of optic flow sensors that are able to measure optic flow sufficiently well for altitude control, and can fit in a package weighing several grams. These sensors, which the author intends to commercialize, make use of a "vision chip", which is essentially an integrated circuit with both image acquisition and image processing on the same die. These sensors have been mounted on smaller Remote-Control (RC) type aircraft and used to perform both altitude control and terrain following over gentler terrain.

Insights from biology are also inspiring new flying platforms. Under support from both DARPA and ONR (Office of Naval Research), a joint effort by University of California, Berkeley Professors Michael Dickinson and Ron Fearing is studying the flight control rules and behaviors of the drosophila (fruit fly), and developing a 2cm wingspan "micromechanical flying insect" (MFI). Dickinson is studying the wing-flapping motions and the optomotor reflexes made by the drosophila under different flight environments. Video cameras and machine vision software capture the physical motion of the moving wings. A device dubbed "Robofly," essentially a scaled-up mechanical model of moving insect wings that is inserted in a bath of mineral spirits, imitates the captured motion dynamics. The observed flow currents model the air currents generated by the insect's wings, while stress gauges on the wings estimate the resulting lift.



How optic flow works.

Dickinson's group also uses various experimental chambers to observe the drosophila's flight patterns in response to different environmental stimuli, such as proximity to obstacles or the presence of odors. This includes a virtual reality chamber in which a drosophila is mounted. Force sensors pick up the fly's behaviors (turn, fly forward, land, etc.) in response to different stimuli, and make appropriate changes to the visual field. This setup creates a closed control loop that allows the fly's response dynamics to be studied. Finally, a 6-degree of freedom robot gantry system is used to simulate observed obstacle avoidance and flight path behaviors. This research is discovering flight control behaviors that will be inserted onto the MFI robot, and ultimately onto future MAV systems.

Fearing's group is fabricating the actual MFI robot. Two piezo-actuators, coupled through a mechanical differential, drive each micromachined wing. The wings are driven at mechanical resonance to maximize propulsion efficiency. The force generated by one wing is currently sufficient to move a rotating boom on which the wing is mounted. At the time of writing, all the novel physical and electrical components have been fabricated. Remaining tasks include system integration and the development of control rules for flight. Fearing expects to demonstrate tethered flight in 2002 and free flight in 2003. The finished MFI will fly about 2 meters/second using solar power.

These technologies are still considered exotic. But as they are further developed, they could find applications in deployed autonomous unmanned systems.

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Other Web links are as follows:

- Dan Koditschek, RHex
  http://ai.eecs.umich.edu/Rhex
- Michael Dickinson, U.C. Berkeley (fruit fly research)
  http://ist-socrates.berkeley.edu/~flymanmd
- Mandyam Srinvivasan, ANU (honey bee research and robot algorithms)
  http://cvs.anu.edu.au/insect/insect.html
  http://cvs.anu.edu.au/bioroboticvision/brv.html