Proc. 4th Int. Conf. On Climbing and Walking Robots, Berns and Dillmann eds., Prof. Eng. Pub., 69-76, 2001.

Insect Designs for Improved Robot Mobility

Roger D. Quinn, Gabriel M. Nelson, Richard J. Bachmann, Daniel A. Kingsley, John Offi, and Roy E. Ritzmann
Mechanical Engineering and Biology, Case Western Reserve University, Cleveland, Ohio, USA

SYNOPSIS

This paper reviews work performed in the Biorobotics Lab at Case Western Reserve University. Our goal is to use intelligent biological inspiration to develop robots with mobility approaching that of legged animals. We have produced a series of robots that have mobility increasingly more similar to that of cockroach. Some of our other projects use more simplified designs and benefit from more abstract biological principles. A new robot uses one drive motor and its gait changes passively so that it walks at high speed in a tripod gait and climbs obstacles with its legs in-phase.

1 INTRODUCTION

The goal of our work in the Biorobotics Laboratory is to use insect mechanical and control system designs as inspiration for the development of robots with improved mobility and mission capability. We use intelligent inspiration rather than trying to mimic the animal, which is not always possible or desirable (1). Available technology often makes it infeasible to copy an animal's systems. For example, electrically actuated artificial muscle is not yet available. Furthermore, considering our goals, there is no reason to model an animal's systems that do not contribute significantly to its mobility.

The mobility of animals, including many insects, is typically superior to current legged robots. This fact recommends the use of animal designs in robots. However, the reality of current technology often encourages engineers to use different designs for legged robots than those found in nature. Some robots use mechanisms to couple their joints for the purposes of reducing the number of actuators or simplifying the control problem. Actuators are typically heavy and reducing their number can increase the payload or range of a robot. When early legged robots were developed, computational limitations impeded the use of onboard computers to coordinate many joints. The ASV (2), Titan IV (3) and Dino (4) are three of many robots that use pantograph mechanisms to uncouple the vertical and horizontal motions of their feet. Dante II used power screws to achieve large forces with small motors to save weight, but this resulted in slow movement (5). The K^2T crab robot used cables, brakes and clutches to move its 17 joints with just 5 motors (6). RHex is a recent robot that adheres to this strategy of simplified mechanical design (7). It uses just one motor in each of its six legs to drive each foot in a circular path. It speeds each foot through its swing phase relative to its stance phase so that the robot can walk in insect gaits despite its simple mechanical design. Mechanical coupling and simplicity can ease the development of legged robots. However, the tradeoffs include reduced mobility. For example, Dino is 13 feet tall but can only lift its feet 19 inches (4). Also, RHex cannot vary the location of its foot placement relative to its body to reach onto obstacles in a variable manner or search for footholds.

There are two design methodologies that a robot designer can follow when using biological inspiration (8). Using simplifying mechanisms to implement abstract biological principles can lead to workable solutions in the near term. On the other hand, following animal designs more closely promises greater mobility, but this approach requires more effort. Biological inspiration can be used to reap rewards in both cases. For example, our Robot II (9), which is loosely based upon stick insect, and RHex, which is greatly simplified, both benefited from passive compliance in their legs, which is known to be important in animal locomotion (10).

This paper reviews different projects in our lab that reflect both of these methodologies. First a series of robots is described that are each successively more similar to a cockroach and promise superior mobility and mission capability. Then two different robots are described that were designed with biological inspiration but using gross simplifications.

2 A SERIES OF ROBOTS THAT ARE PROGRESSIVELY MORE SIMILAR TO A COCKROACH

Our Robot I and Robot II are both hexapods that used DC motors with their power and control systems off board. Robot I had two degrees of freedom (DOF) in each of its identical legs and its purpose was to walk on smooth terrain and demonstrate gait controllers (11). It walked in a continuum of insect gaits using biologically inspired networks (12, 13). Robot II had three revolute DOF in each of its six identical legs, which gave it a sprawled, insect-like posture (9). Its distributed control system used local joint and leg circuits, leg reflexes, the stick insect network (14) for gait generation, and a central posture controller. This remarkably simple control system gave Robot II impressive mobility capabilities. It walked in a continuum of insect gaits, turned, and walked sideways, over irregular terrain and on slatted surfaces (15).

Other researchers have developed similar robots using DC motors. Genghis (16) and Hannibal (17) preceded Robots I and II and were of similar size and configuration, respectively. Built concurrently with Robot II, the TUM robot had similar kinematics and some of the same mobility capabilities and it had the advantage of being self-contained (18). More recently an eight-legged robot named

SCORPION has been developed with leg kinematics similar to Robot II's (19). It is self-contained and has a distributed control system similar to Robot II's, with a subset of its leg reflexes.

DC motors are readily controllable but their force to weight ratio is less than desirable for a mission capable robot. Autonomous robots using them tend to be slow. Pratt et al. overcame some of the disadvantages of DC motors by placing springs in series with them (20). Binnard developed a hexapod robot that was inspired by cockroach and it was actuated with air cylinders, which offer a greater force to weight ratio (21). For this reason we chose to use them to actuate Robot III.

Robot III captures the leg kinematics of cockroach responsible for its agility in walking, turning, running and climbing over barriers. We used the methodology of intelligent biological inspiration so that the robot would have the minimum complexity to accomplish the desired behaviours in a cockroach-like manner (22). For this purpose we documented the locomotion behaviour of the *Blaberus discoidalis* cockroach and extracted the salient features important for locomotion using dynamic simulation.

Side and ventral views of cockroaches walking on a treadmill (Fig. 1) and climbing were recorded using high-speed video at 250 frames per second, and joint trajectories were extracted from the data (23, 24). A dynamic model of a cockroach was developed in which each leg was simplified to have three segments (24). We found that each leg pair can perform its intended function in executing walking and climbing behaviours with the rear, middle and front legs reduced to three, four and five DOF, respectively. The cockroach model was scaled up in length by a factor of 17 to represent the robot. The structure of Robot III was designed to withstand loads predicted by the model and its air cylinders were sized to produce the predicted joint torques.

A robust centralized posture controller has been demonstrated and the robot has been shown to lift a payload equal to its own 13.6kg weight (25). The swing controller consists of a hierarchy of joint, leg and gait controllers. A localized proportional controller causes the joints to follow a desired trajectory. The inverse kinematics problem is implemented in a neural network that coordinates the joints in a leg (26). The stick insect distributed network (14) is used to coordinate the legs of the robot. The swing controller has been demonstrated to cycle the legs smoothly in a tripod gait with each foot moving in a pattern similar to that observed in the cockroach (Fig. 2).

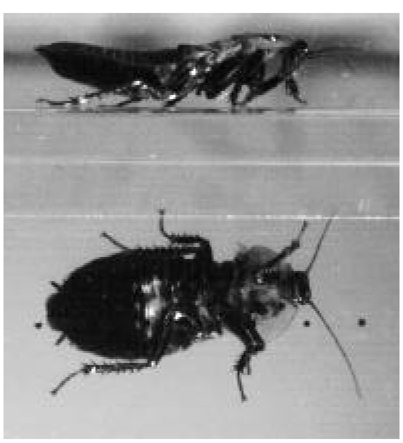


Figure 1. Cockroach on treadmill

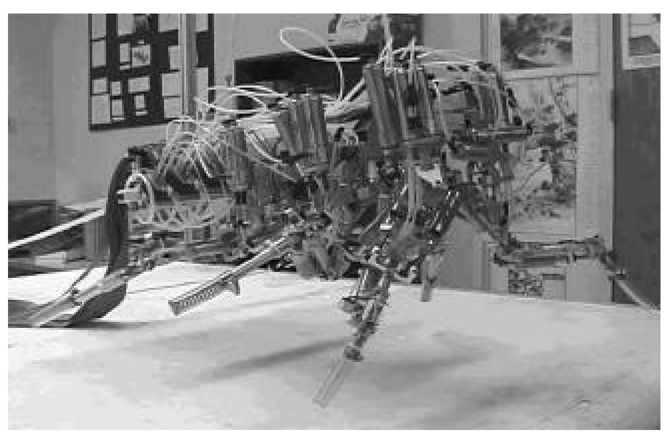


Figure 2. Robot III cycling its legs in tripod gait

Other research groups have concurrently developed pneumatically actuated robots. Although it has fewer DOF than Robot III, Protobot is also based upon the cockroach and the robot is actuated with air cylinders (27). Robug IV has eight identical legs, each with three DOF, and it uses air cylinders (28). Air can be trapped in the air cylinders so that its joints can have passive stiffness and it does not need to expend air to stand.

Robot III has the agile leg designs and strength needed for a mission capable robot. However, its power source and controller are off board. Also, its three-way valves make it impossible to trap air in the cylinders and thereby attain passive joint stiffness, which is important for energy efficient legged locomotion.

Robot IV has been designed to be capable of energy efficient locomotion. Its leg kinematics are the same as those of Robot III and its joints have passive stiffness that can be tuned appropriately to take advantage of energy storage during a step cycle.

An actuator with certain properties that are similar to those of muscle can be most effective for legged, animal-like vehicles. Braided pneumatic actuators, also known as McKibben artificial muscles or Rubbertuators, have several of these desirable properties (29, 30). They can apply tension, have a higher force to weight ratio than motors or air cylinders, are structurally flexible, and their force output is self-limited. Furthermore, when they are used in antagonistic pairs, a joint's stiffness can be tuned independent of its motion. Air cylinders share this property, but McKibbens are more easily tuned over a wider range of conditions. Powers developed the first hexapod robot that used braided pneumatic actuators (31).

Robot IV will use antagonistic pairs of McKibben artificial muscles, whose structural flexibility permits insertion into the robot's exoskeleton structure. Prototype front legs of Robot IV, with McKibbens installed, have been attached to a frame with wheels to form a hybrid wheel-leg robot (32). When its actuators are pressurized, this hybrid robot stands (Fig. 3). A CAD drawing of the hexapod Robot IV is shown in figure 4.

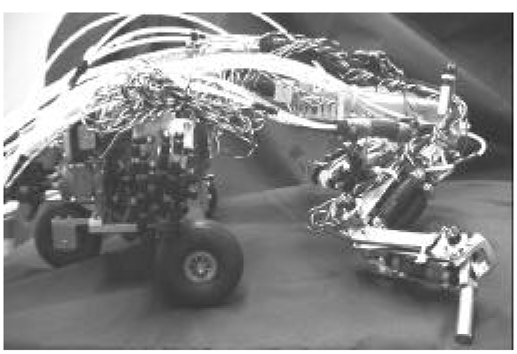


Figure 3. Robot IV front legs on hybrid robot

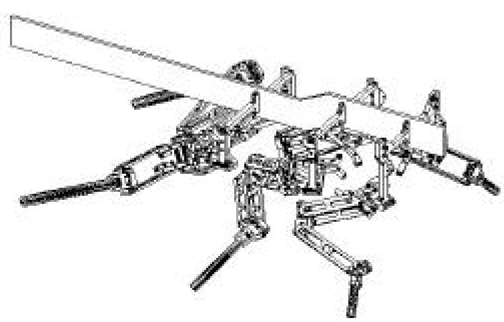


Figure 4. Robot IV design

While Robot IV was being designed and fabricated, we investigated ways of controlling McKibben actuators by tuning their passive stiffness. A simple leg with two joints was constructed with McKibben actuators (Fig. 5). The leg was suspended from a horizontal track so that it could cycle during swing, then push the trolley forward in the stance phase. Results indicate that it should be able to walk with its valves closed 90% of the time (33). This demonstrated the promise of energy efficiency with McKibben actuators.

3 ROBOTS DESIGNED WITH ABSTRACTED BIOLOGICAL PRINCIPLES

We are also developing a self-contained 7.5cm long robot based upon cricket that will locomote by walking and jumping (34). The small size and autonomy of this vehicle required that we design and fabricate most of its components. An 8mm motor drives a miniature on-board compressor that supplies air to valves that were fabricated using a MEMS process. The valves inlet and exhaust air for small custom built McKibben actuators. Neural network controllers are being evolved for the robot using genetic algorithms. The controller is currently implemented with a PIC, but analog VLSI circuits are being developed for this purpose. A hybrid wheel-leg robot has been demonstrated that can walk with all its components on board (Fig. 6). The rear leg designs are inspired by those of the cricket, but with many simplifications.

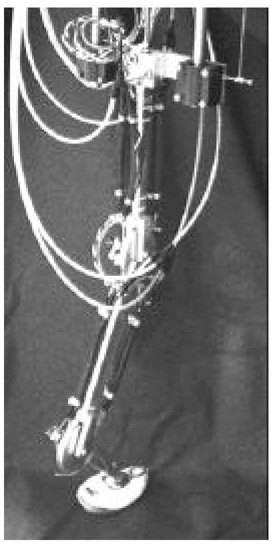


Figure 5. Two DOF leg with McKibbens

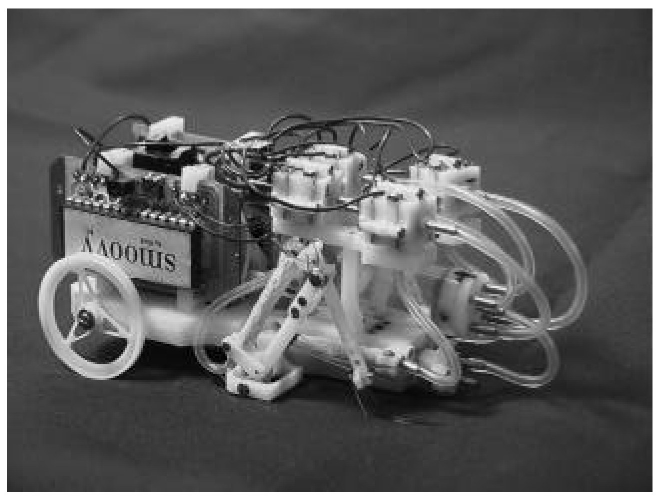
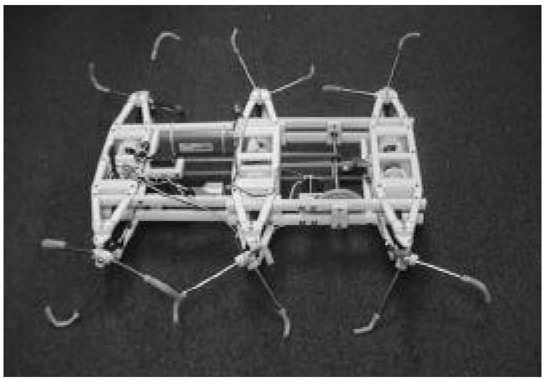


Figure 6. Small hybrid wheel-leg robot

We have recently developed a simple robot that benefits from abstract biological inspiration and has good walking and climbing capabilities. This new vehicle is shown in figure 7 and is called Whegs (© R. Quinn, Patent Pend.). It has a single drive motor and two small servo motors for steering. The biological principles that are incorporated into its design include a nominal tripod gait that passively changes on irregular terrain and evolves into co-activation of legs for climbing. It also has the capacity to place its front legs on top of large objects for climbing.

Whegs uses a hybrid of wheels and legs that we call "whegs." It has six whegs and nominally walks in a tripod gait. In the case of this vehicle, the whegs have a tri-spoke configuration. The three spoke wheg design is optimal relative to one, two, four or more spokes when smoothness of ride and climbing abilities are both considered. Even if the whegs are rigid, the three spoke design only causes the axle to travel vertically 13% of the spoke length when the vehicle is moving in a tripod gait on smooth ground. This is in the range of the typical vertical body motion of a cockroach in the same conditions. A two-spoke design would cause the axle to move excessively, whereas a four or more spoke design would result in a smoother ride. If a front foot reaches the top of a barrier as shown in figure 7b and the motor is strong enough, the robot can climb over the obstacle. Ignoring the interference of the opposing front wheg, the three-spoke design can climb nearly as well as the two-spoke design and much better than a four or more spoke design. Therefore, the three-spoke design is optimal. Furthermore, the vertical motion can also be reduced by incorporating radial compliance into the whegs as has been done previously in our Robot II (9) and more recently in Bheuler et al.'s RHex (7). Another advantage to the wheg design is that while RHex's six motors must accelerate and decelerate while the robot runs at constant speed, Whegs' single drive motor runs at constant speed given a constant robot speed. This is more energy efficient. Steering the Whegs robot is accomplished by rotating the front and rear whegs as with a wheeled vehicle. This alters the placement of the feet and causes the robot to steer, which is also how the cockroach turns.



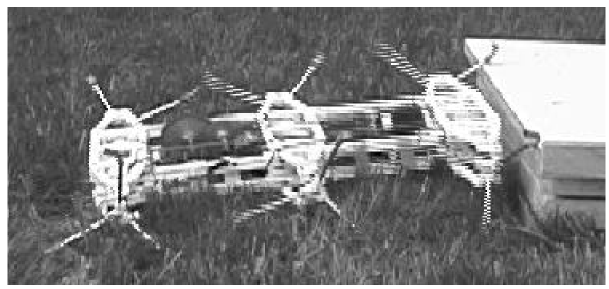


Figure 7a. Whegs uses tri-spoke appendages b. Whegs climbing a 15cm obstacle

Whegs' one drive-motor design is beneficial because the maximum onboard torque can be delivered to any leg. When different motors drive different legs, the maximum torque available to drive a single leg is restricted to that available from one of the many motors. The single motor design permits the use of a larger motor for the same total motor weight and, therefore, a greater available torque at any leg. This greater leg torque capacity reduces the chance of stall, for example, when the vehicle is climbing. For this same reason, the single motor design can have equal climbing abilities with less overall motor weight. As described above, the reduction of motor weight is important for increasing the payload and range of legged robots.

When a cockroach climbs a small rectangular obstacle, it does not need to alter its tripod gait. However, when the obstacle is about shoulder high or taller, the cockroach changes its leg motions and moves its legs in phase. The hexapod Whegs similarly can climb small barriers without changing its gait. When a larger obstacle is encountered the opposite front wheg can interfere with the obstacle and not let the front wheg reach the top of the obstacle. For this purpose, we incorporated passive compliance into the axles of the whegs. When a large obstacle is encountered the whegs passively move into phase from their nominal out-of-phase tripod gait (Fig. 7b). Results of this compliance are that the robot passively changes its gait as it walks over natural terrain and its climbing ability is enhanced. It has climbed a rectangular obstacle that had a height of 75% of the wheg diameter using the in-phase leg gait. At high speed the robot uses the tripod gait and walks with little vertical body motion. Its climbing ability is an improvement on wheeled vehicles, but a legged robot more closely based upon cockroach could do better.

4 SUMMARY

Intelligent biological inspiration can benefit both simple and more animal-like designs. In both cases, those aspects of an animal's mechanics that are deemed important for the mode of locomotion of interest are implemented into the robot design. If a robot's design more closely resembles the animal, the animal's mechanisms can be more directly installed into the robot. Disparities between current technology and that found in the animal can limit this approach. Given this limitation, we can either engineer solutions to advance the technology, allowing for more animal-like robots, or we can make simplifications to the robot's design so that the current technology may be easily applied. The animal-like design promises greater mobility, but requires more effort to produce. The other approach sacrifices mobility for simplicity. This paper reviews a series of robots that are increasingly similar to cockroach. Each new robot represents an advance in mobility or efficiency. Two other biologically inspired robots are also reviewed that have greater simplifications incorporated into their designs and are self-contained. The microrobot has cricket inspired legs on its rear and wheels on its front. A new vehicle called Whegs has simplified legs and its nominal tripod gait passively changes with changes in the terrain. Its legs move in-phase during climbing as has been reported for cockroaches in the same circumstances. This work was supported by the Office of Naval Research (N0014-99-1-0378) and DARPA (DAAN02-98-C-4027).

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