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Toward Mission Capable Legged Robots through Biological Inspiration

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Abstract. Insects provide good models for the design and control of mission capable legged robots. We are using intelligent biological inspiration to extract the features important for locomotion from insect neuromechanical designs and implement them into legged robots. Each new model in our series of robots represents an advance in agility, strength, or energy efficiency, which are all important for performing missions. Robot IV is being constructed with a cockroach mechanical design. It features a lightweight exoskeleton structure and McKibben artificial muscles for passive joint stiffness. Our self-contained microrobot has rear legs that are inspired by cricket. Its diminutive size required us to custom fabricate almost all of its parts, including its McKibben actuators.

Keywords: biorobots, neuromechanics, cockroach, McKibben artificial muscle, cricket, pneumatic

1. Introduction

A robot's mechanical design and choice of actuators should fit the robot's mission. Dante II is possibly the most well-known legged robot that performed a mission (Bares and Wettergreen, 1999). This large eight-legged vehicle successfully descended into a volcano, collected samples, and climbed part of the way out. To reduce weight, the robot used small motors with large transmissions and it was therefore slow. Other robots use fewer motors than they have joints to reduce weight and increase payload or range. Clutches, brakes and cables were used to drive the 17 joints of the K^2T eight-legged walker from its 5 motors (Flannigan et al., 1998). Various mechanisms are often used on legged robots to reduce leg weight and to simplify the control problem. The ASV is a large hexapod that uses pantograph mechanisms to uncouple horizontal and vertical foot motions (Song and Waldron, 1989). Similarly, Dino, a large quadruped, uses mechanisms on its legs which allow its motors to be placed on the body, keeping its legs relatively lightweight (Saunders, 2001). This approach can limit agility. For example, Dino is 13 ft tall but can only lift its feet 19 inches. Dino is a successful robot because it satisfies its mission, which is entertainment. Different actuators may better suit different missions. Dino was initially going to use hydraulics with an internal combustion engine like the ASV, but was changed to use electric motors and batteries because of noise considerations and the desire for indoor operation. Shape memory alloys may be best suited to actuate legged robots performing underwater missions (Ayers, 2000).

Despite decades of work, engineers are far from developing a legged robot that rivals the agility and efficiency of animals. Clearly much can be learned from nature and applied to this design problem. However, it is not always technologically feasible or desirable to mimic the neuromechanical design of an animal. Any design must take into account the differences in the technologies. For example, unlike muscles, electric motors are not efficient when forced to periodically accelerate. This explains the use of mechanisms to drive the joints in many robotic leg designs that use motors. RHex uses one motor for each of its six legs and swings each foot in a circular path (Saranli et al., 2000). This is not the way an animal solves the problem, but it is a good use of motors. Pratt solves the problem by using a spring in series with each motor so that the robotic joints are passively compliant and can cycle like animal joints (Pratt et al., 1997).

The goal of our work is to develop agile legged robots that can perform missions in rugged environments in natural terrain on Earth or on extraterrestrial surfaces. These missions can be expected to require the robot to locomote autonomously over and through rocky terrain or rubble while carrying a payload. Legs promise superior mobility for a vehicle of a given size. However, there are many challenges to the development of a mission capable legged robot. Its structure and actuators must be strong and lightweight and the robot's design should give it agility so that it can climb over obstacles and through irregular terrain. It must also be energy efficient so that it can function autonomously long enough to accomplish a useful mission. Insects have all of these attributes and we are learning from their designs. However, our strategy is not mimicry. Instead, we attempt to capture the important neuromechanical principles for the forms of insect locomotion that we wish to implement in our robots; we refer to this process as intelligent biological inspiration.

2. A Series of Robots Each More Similar to a Cockroach

Robot I had six identical legs, each with two joints, and it walked on smooth terrain in a continuum of insect gaits using two different gait controllers, one of which was a network of influences derived from stick insect behavior (Espenschied et al., 1993). Robot II had three revolute degrees of freedom (DOF) in each of its six identical legs, which gave it a sprawled, insect-like posture (Espenschied et al., 1996). Its distributed controller included local joint position controllers, leg controllers with localized reflexes, a gait controller based upon the stick insect mechanisms (Cruse, 1990), and a central posture controller that positioned and oriented the body. It could walk and turn on irregular terrain, including slatted surfaces, and was robust to disturbances (Espenschied et al., 1995). While Robot II was not self-contained (it had a tether), Klaassen et al. have implemented a controller with some of Robot II's attributes into a self-contained eight-legged robot that also uses DC motors.

Our first two robots were actuated with DC motors and while these motors are readily controllable, their force to weight ratio is less than desirable for a mission capable robot. Binnard (1995) developed a hexapod robot that was inspired by cockroach and it was actuated with air cylinders, which offer a greater force to weight ratio. For this reason we chose to use them to actuate Robot III.

Robot III was designed to capture cockroach leg kinematics for the purpose of giving it the agility to walk, turn, run, and climb over barriers. Its structure and actuators were designed to give it strength for quickly climbing inclines and barriers while carrying a payload (Bachmann et al., 1998). We used the methodology of intelligent biological inspiration so that the robot would have the minimum complexity to accomplish the desired behaviors in a cockroach-like manner. For this purpose we documented the locomotion behavior of *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. Body motions and joint trajectories were extracted from the data (Watson and Ritzmann, 1998; Nelson, 1995). Dynamic simulations were used to show that the rear, middle, and front legs could be reduced from 7 joint DOF for each leg to three, four and five, respectively. Despite these simplifications, each leg pair can perform its intended function in executing the desired walking and climbing behaviors. The cockroach simulation 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 posture controller has been demonstrated and the robot (Fig. 2) has been shown to lift a payload equal to its own 13.6 kg weight (Nelson and Quinn, 1999). The swing controller, which cycles the legs in a cockroach-like manner, 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. The stick insect distributed network

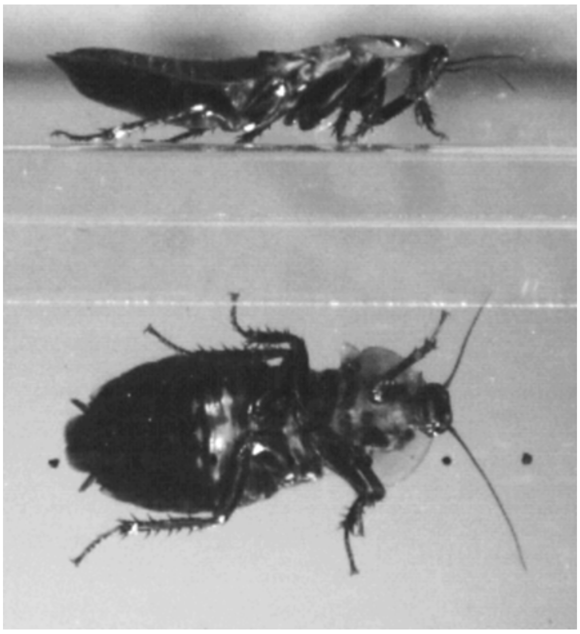

Figure 1. A cockroach running on treadmill with a translucent belt. A camera records the side and ventral (from a mirror under the treadmill) views simultaneously.

(Cruse, 1990) coordinates the legs. The legs have been demonstrated to cycle smoothly in a tripod gait with each foot moving in a pattern similar to that observed in the cockroach.

Robot III has the agile leg designs and power needed for a mission capable robot. However, its power source and controller are off board. Also, its use of three-way valves makes it impossible to trap air in the cylinders and thereby attain passive joint stiffness.

Other research groups have also developed pneumatically actuated robots. Protobot's geometry is based upon a cockroach and it is actuated with air cylinders (Delcomyn and Nelson, 1999). Robug IV is an eight-legged robot that uses air trapped in its cylinders so that its joints have passive stiffness and it does not need to expend air to stand (Cooke et al., 1999). This feature is important for energy efficiency and we are incorporating it in our future robots.

Continuing toward the goal of mission capability, Robot IV has been designed to be capable of energy efficient locomotion. Its leg kinematics are more similar to those of the cockroach than those of Robot III, and its actuators 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 vehicles. Braided pneumatic actuators, also known as McKibben artificial muscles or Rubbertuators, have several of these desirable properties (Nickel et al., 1963; Chou and Hannaford, 1996). 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 also share this property, but McKibbens are more easily tuned over a wider range of conditions. Powers (1996) developed the first hexapod robot that uses braided pneumatic actuators.

Robot IV will use antagonistic pairs of groups of McKibben artificial muscles and their structural flexibility will permit their insertion into its

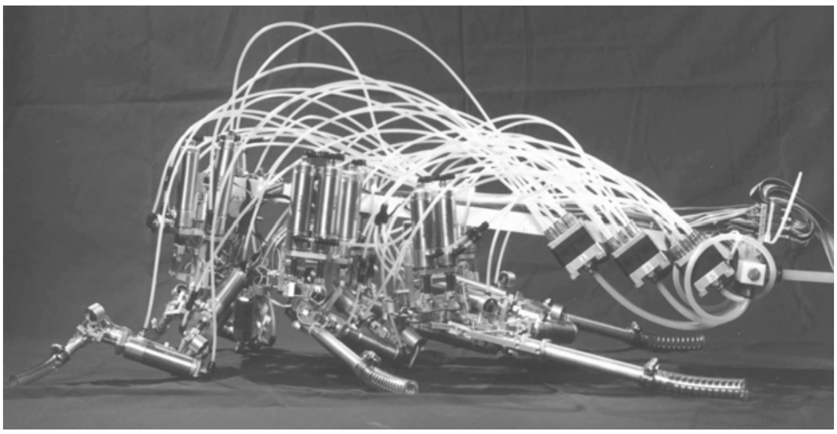

Figure 2. Robot III.

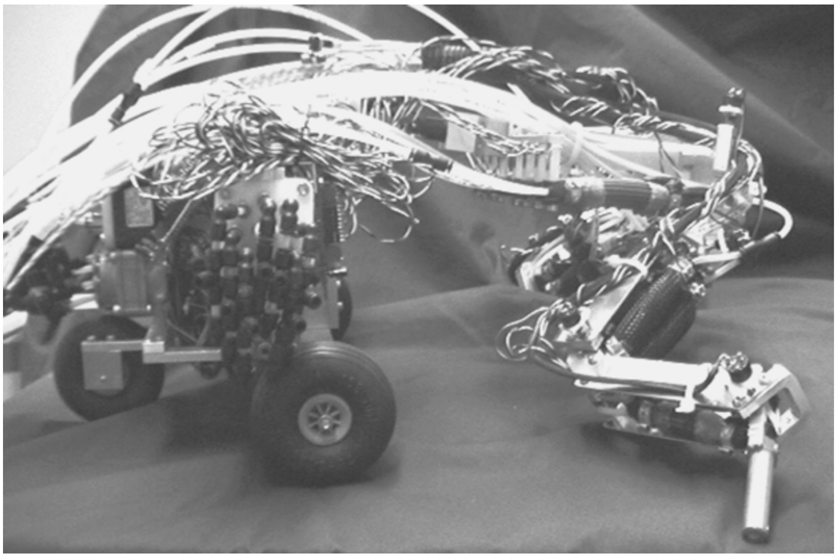

Figure 3. A large hybrid wheel-leg robot stands using McKibben artificial muscles. The front legs are prototype front legs for Robot IV.

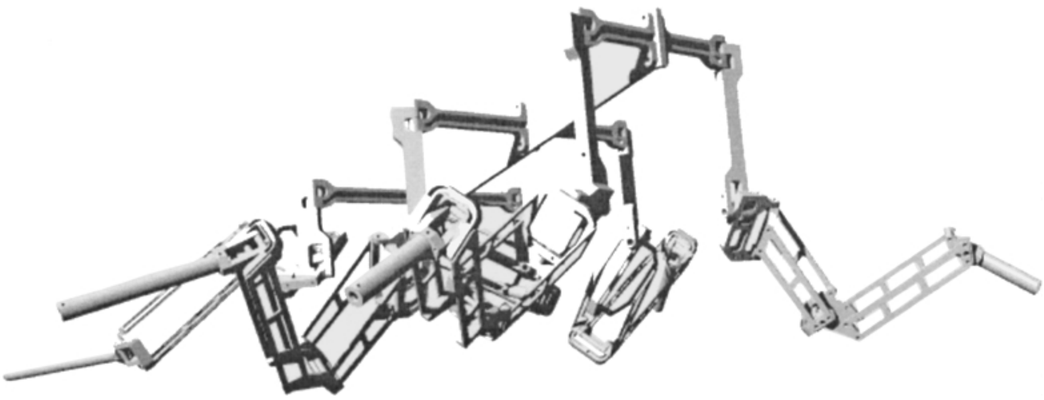

Figure 4. Right, front, bottom view of the Robot IV design.

exoskeleton structure. Robot IV prototype front legs, with McKibbens installed, have been attached to a frame with wheels to form a hybrid wheel-leg robot (Kingsley, 2001). When its actuators are pressurized, this hybrid robot stands (Fig. 3). A CAD drawing of the hexapod Robot IV is shown in Fig. 4.

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). It was suspended from a horizontal track so that it could cycle its leg in swing and then push the trolley forward in the stance phase. Results indicate that it should be able to walk while the valves are off 90% of the time (Colbrunn et al., 2001). This promises energy efficient locomotion.

3. A Micro Robot Inspired by Cricket

We are also developing a self-contained three-inch long robot based upon cricket that will locomote by walking and jumping (Birch et al., 2000). The small size and autonomy of this vehicle required that we design and fabricate most of its components. An 8 mm 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

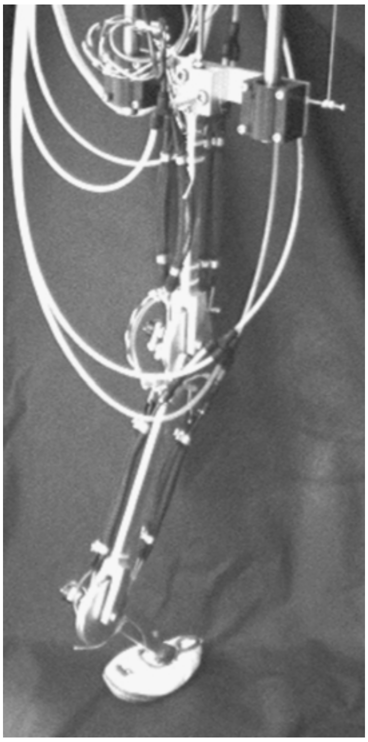

Figure 5. A planar leg with McKibben artificial muscles.

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 walked with all its components on board (Fig. 6).

4. Summary

The purpose of our work is to develop agile, mission capable legged robots. A robot with the agility and energy efficiency of a cockroach could accomplish many different types of exploratory missions on earth and on extraterrestrial surfaces. Therefore, we are using intelligent biological inspiration to advance towards this goal using insects as models. Technological differences make it infeasible or undesirable to mimic certain aspects of the animal. Reproducing the locomotion behaviors of the animal is most important. Each of our robots represents an advance over the previous generation and a potential improvement in its agility, strength, and/or autonomy. Robot I walked with insect gaits, Robot II walked on irregular terrain, Robot III has the strength and potential agility needed for

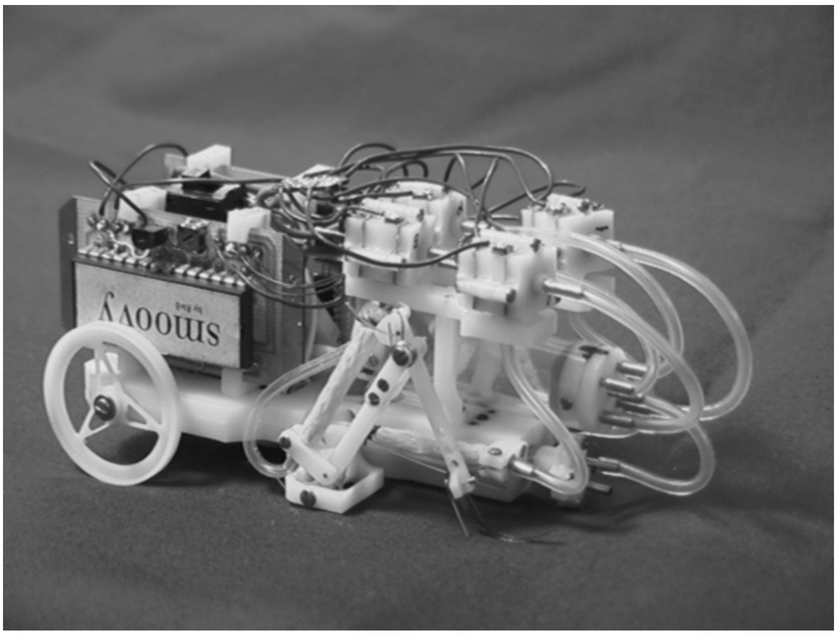

Figure 6. A small, self-contained hybrid wheel-leg robot with McKibben artificial muscles. The rear leg design is inspired by cricket legs.

climbing efficiently over obstacles, and Robot IV is designed to capture the agility of Robot III with the addition of energy efficiency. The hybrid wheel-leg microrobot is an advance in autonomy and size. Its diminutive size can be an advantage for missions that require stealth or autonomous locomotion through small spaces.

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