

Construction of a Hexapod Robot with Cockroach Kinematics Benefits both Robotics and Biology

ROGER D. QUINN & ROY E. RITZMANN

*Any device that moves by actuating several multi-segmented legs must solve fundamental problems in mechanics and control regardless of whether that device is made out of living tissue or metal. With this in mind, we believe that advances can be made both in the design of legged robots and in understanding how legged animals locomote by working on these issues in tandem. This basic philosophy has led us to build a hexapod robot with kinematics that are remarkably similar to those of the death head cockroach *Blaberus discoidalis*. This effort has required us to make detailed neurobiological and kinematic observations of cockroaches walking on a treadmill and climbing over barriers. The data acquired in this way were then input to our dynamic simulation tool to determine mechanically accurate parameters for the design of the robot. The resulting vehicle captures the cockroach kinematics so well that issues that are being addressed in controlling it are providing important notions regarding the neural control of locomotion in the animal. Thus, the project has led to benefits in both directions. Biological data inspired the initial design of the robot, while engineering efforts in control are inspiring further neurobiological experiments in animal locomotion.*

KEYWORDS: Biorobotics, *Blaberus*, dynamic simulation, legged locomotion, walking, climbing.

1. Introduction

The goal of this project was to demonstrate the advantages of careful biological emulation in robot design. The robot would be used as a platform on which biologists and engineers could test hypotheses about cockroach posture and locomotion. We did not intend to build a robot with all of the remarkable locomotion capabilities of the cockroach. The state of actuator and power source technology precludes this. Therefore, we limited the locomotion goals of Robot III to walking, turning and climbing in a manner similar to a cockroach. To determine the aspects of the insect's legs and their control that are critical to those behaviors, we made detailed kinematic and neurobiological observations of the animal while it was performing those tasks.

In this paper, we first describe the biological observations that were made, providing detailed kinematic data on cockroaches running on a treadmill and climbing over barriers. We then describe how those data were incorporated into a dynamic simulation which predicted motor and structural loads that were used in

the design of the robot. Finally, we describe the construction of the robot and development of its posture controller. The posture controller is an important part of the locomotion controller that is currently under development.

2. Biological Observations

In order to collect the necessary data on the mechanics of cockroach walking, our first task was to build a walking platform that would allow us to monitor the movements of all leg joints as the animal performed real walking movements. Considerable work had been done in the past on cockroach walking (Delcomyn, 1971, 1985; Pearson, 1976; Pearson & Iles, 1970; Spirito & Mushrush, 1979). However, most of that work focused upon the timing of foot contact with the ground (i.e. footfall patterns). In order to provide accurate information on leg movements and on the control of leg movements, we had to move beyond footfall patterns to monitor individual joint movements.

Fortunately, advances in high-speed video systems made these observations possible. However, an important problem had to be overcome. Insects make complex leg movements in 3D space. Because of the inherent problems associated with viewing a 3D movement projected on to a single plane, any single view could readily generate false data on joint movement. In order to determine accurately joint kinematics, we had to view leg movements from two orthogonal directions, measure the joint angles and then reconstruct the true 3D movements from those data (Biewener & Full, 1992). To accomplish this task, we constructed a miniature transparent treadmill that allowed us to view the animal simultaneously from the side and from the ventral surface (underside), via a mirror positioned at a 45° angle under the belt (Watson & Ritzmann, 1998a) (Figure 1). Video images were taken at either 200 or 250 frames per second. The videotape was then played back frame by frame so that we could digitize specific landmark points on the legs. The digitized data from both views were entered into a custom program along with measurements of the actual dimensions of each leg segment. The program then reconstructed the true angles of the leg joints in three dimensions as the animal moved along the treadmill.

Each cockroach leg is divided into several segments (Figure 4(A)). Although the segments are reproduced in each of the three pairs of legs, their dimensions are very different in the front, middle and rear legs. The leg segments from the most proximal to the most distal segment are called the coxa, trochanter, femur, tibia and a series of foot joints collectively called the tarsus. The joint between the body and coxa is made of two plates with soft tissue between them. The complex musculature coupled with complex mechanics confers upon this joint three degrees of freedom (DOFs) much like that of a ball and socket joint (Laurent & Richard, 1986). The distal joints are for the most part more straightforward. The joints between the coxa and trochanter, between the trochanter and femur, and between the femur and tibia are simple one DOF joints. The joint between the trochanter and femur makes only a small movement and has often been referred to as fused. However, our observations suggest that because of the 45° orientation of the joint coupled with its proximal location on the leg, even the small movement of the trochanter allows the animal to rotate the tibia and tarsus relative to the ground. This movement is important to the actions associated with several movements, especially climbing. The tarsal joints each have several passive DOFs, making for agile foot placement. Finally, a claw located on the end of the tarsus can be raised

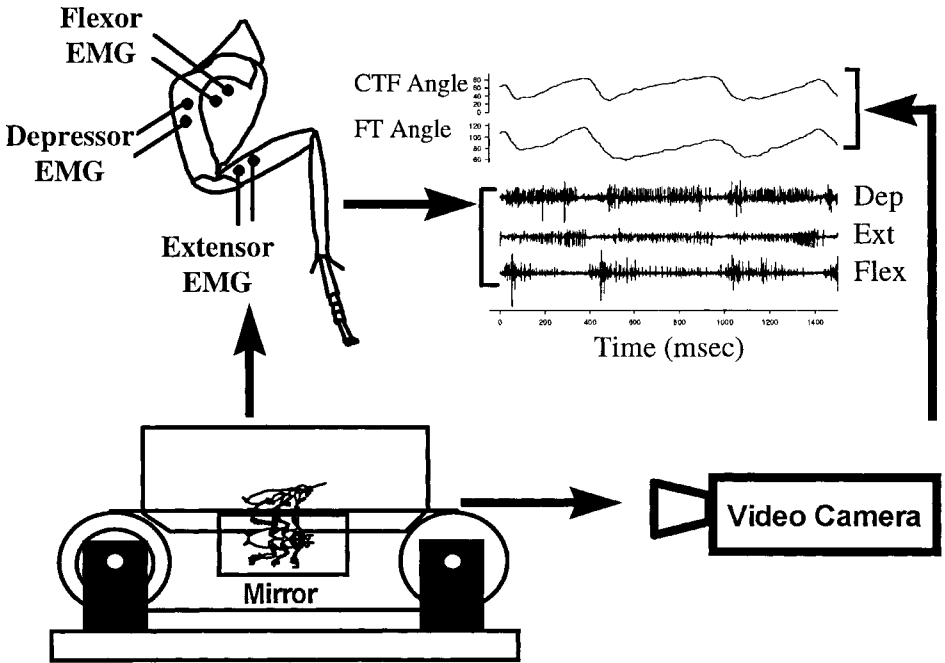


Figure 1. Schematic showing data collection methodology. The leg in the upper left corner shows the placement of insulated wires for EMG recording. The record in the upper right corner shows joint angle data from a rear leg (trace 1 from the coxa–trochanter–femur (CTF) joint and trace 2 from the femur–tibia (FT) joint) combined with three EMGs (trace 3 from the trochanter depressor, trace 4 from the tibial extensor and trace 5 from the tibial flexor).

or lowered to engage the substrate during locomotion on slippery surfaces for climbing.

We also have an interest in the control of the leg joints. Thus, we combined our kinematic analysis with electrophysiological recordings of motor activity (Figure 1). Neuromuscular activity can be readily monitored in a freely behaving animal by recording the electrical currents in the muscle extracellularly (Watson & Ritzmann, 1998a). The resulting records are referred to as electromyograms (EMGs). In insects, this technique is particularly useful because, unlike vertebrates, each arthropod muscle is typically innervated by relatively few motor neurons. For example, the muscles that are believed to provide most of the action in extending the femur of each leg during walking are innervated by only two motor neurons, the fast and slow depressors (Df and Ds, respectively) (Pearson & Iles, 1971). Moreover, muscle records from these two motor neurons are readily distinguished based upon the size of their related EMG potentials. Thus, activity in the muscle can be directly related to activity in specific motor neurons.

In order to make a useful robotic vehicle, we wanted it to be able to walk through complex terrain and interact with its environment in three dimensions. Specifically, the tasks that we wanted the robot to be capable of performing included efficient walking, turning and climbing over objects. We therefore set out to study the leg movements and joint control in horizontal walking at various different speeds, as well as during turning and climbing.

2.1. Horizontal Walking

Even in our initial observations, it was clear that the movements of the three pairs of legs were not similar. The typical gait during most speeds of walking is an alternating tripod gate (Delcomyn, 1971). In this movement the front and rear right legs move in synchrony with the left middle leg, forming a tripod that alternates with the tripod that is made up of the remaining three legs. Although the feet of the three legs move in synchrony, the joint movements of the front, middle and rear legs are distinct. Each leg's joint movements are specialized for unique roles played by each pair of legs. The observation is consistent with data on ground reaction forces, indicating unique patterns of behavior for each pair of legs (Full *et al.*, 1991).

The rear (metathoracic) legs are specialized for producing power to accelerate the animal forward. The movement of the two joints that are responsible for extending the leg, coxa–trochanter–femur (CTF) and femur–tibia (FT) joints, occurs in synchrony, moving through approximately the same excursion in both joints (Watson & Ritzmann, 1998a) (Figure 1). As a result, the tarsal segments are driven directly backward in a line essentially parallel to the animal's long axis providing powerful forward propulsion on the body (Figure 2).

In the middle (mesothoracic) legs, the two joints also move synchronously, but the FT joint goes through a smaller excursion than the CTF joint (Watson & Ritzmann, 1998a). This movement, along with the orientation at the body coxa joint, results in a sweeping movement, which first decelerates and then accelerates the animal (Full *et al.*, 1991). Other observations described later on suggest that the middle legs are particularly important in turning the animal and in climbing movements.

The front (prothoracic) legs are the most unique. To form a functional tripod movement, the tarsus of these legs must extend forward during swing and then be pulled rearward, while the middle and rear legs of a given tripod extend rearward. To do this the front leg must make much more use of the body–coxa joint to swing the coxa forward than is seen in the middle and rear legs. With the forward swing of the coxa and the required forward movement of the tarsus, the CTF and FT joints must come out of synchrony to make the appropriate foot placement. Indeed, in some cases these two joints actually move in antiphase (Watson *et al.*, 1996).

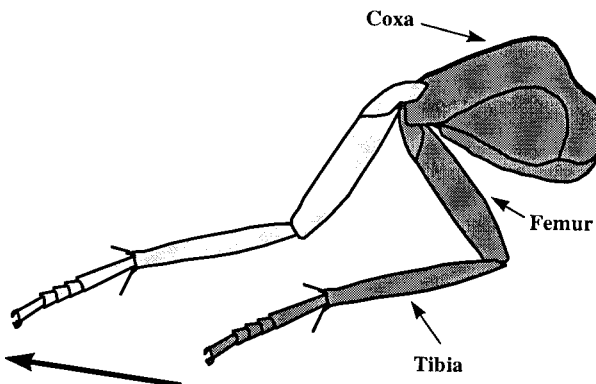


Figure 2. Movement of rear leg showing how equal movement of the coxa–femur joint and the femur–tibia joint results in powerful rear-directed movement.

Although the movement made by the prothoracic legs is complex, it can be at least partially visualized by realizing that, unlike the other two pairs of legs, the front legs are extended during swing. Then during stance phase, they are drawn back toward the body and then extended again. The first part of the stance movement is accomplished by flexing the FT joint while extending the CTF joint and rotating the coxa backward. As the tarsi are drawn under the body, the FT joint stops flexing and the CT joint continues to extend, pushing the tarsi rearward. During swing the process is essentially reversed, while the leg is lifted off the ground.

Also, unlike the middle and rear legs, the movements of the front legs are somewhat variable. Indeed, the forward projection and variability of the prothoracic leg movements are reminiscent of human arms, suggesting that they may be used as sensorimotor appendages for investigating the local environment.

The different joint movements found in the three pairs of legs should be associated with equally different motor activity. This was found in the related EMG records (Watson & Ritzmann, 1998a). In the rear legs, activity in the Ds, which controls extension of the CTF joint, occurs in near synchrony with activity from the slow extensor of the tibia (SETi), which controls extension of the FT joint (Figure 1). In the middle legs the two motor neurons are also in synchrony, but SETi is active at a lower frequency consistent with the smaller movement at the FT joint in that leg. In the prothoracic legs, activities in DS and SETi are not in synchrony (Watson *et al.*, 1996). Rather, SETi fires before Ds to produce the initial FT flexion. After the FT flexion and as the CTF joint is extending, there is a second lower frequency burst in SETi. This occurs as the leg is passing under the animal's body. It is consistent with the hypothesis that, at this point, the front leg is being loaded and a small amount of tension is required in the FT joint to prevent collapse of the leg. This burst could result from a reflex initiated by sensory receptors called campaniform sensilla (Zill, 1990; Zill & Seyfarth, 1996) that are located in the leg's cuticle and detect cuticular strain such as would occur during loading.

2.2. Change in Walking Speed

In order to walk faster, the cockroach increases the velocity of joint movement, in particular in the stance phase (depression and extension of joints). This change is accomplished by increasing the rate of activity in the slow motor neurons that control movement of those joints (Watson & Ritzmann, 1998a). In fact there is a linear relationship between the firing rate of Ds and SETi and the related joint velocity. At very high speeds, the second motor neuron that controls each of these joint movements is recruited. These neurons are called the Df and the fast extensor of the tibia (FETi). They are easily distinguished from the slow motor neurons because they generate much larger muscle potentials in the EMG records (Watson & Ritzmann, 1998b).

In response to activity in Df, the CTF joint appears to become much stiffer (Watson & Ritzmann, 1998b). The joint rebounds more rapidly from swing to stance, thus shortening the transition time. Timing of activity in Df comes at the right time for this change in transition duration to occur. Stiffening of the CTF joint appears to be an important event for walking at any speed. The Df potential occurs at the same time in which Ds normally fires a high-frequency burst. Thus, it appears that at this time of transition it is very important for the joint to become stiff in expectation of the increased load during foot touchdown, regardless of walking speed. A similar high-frequency burst has also been found at the onset of

extensor activity in cats (Gorassini *et al.*, 1994). Finally, joint stiffening at touch-down was found to be a critical problem that has to be overcome in walking movements of Robot III. This observation is just one example of where hurdles that have to be overcome in Robot III point to an explanation for universal properties of legged locomotion in animals.

2.3. Turning

In order to turn, the cockroach must create a mismatch in joint movement in the right and left legs that at any given time is generating forward-directed force. This can be accomplished by altering the velocity of movement in the middle leg relative to the activity of the rear leg of the same tripod. For example, to turn to the right the animal would increase the activity in the left middle leg relative to the right rear leg. However, if the alternate tripod were on the ground it would turn towards the middle leg by decreasing activity in the right middle leg relative to the left rear leg. Observations of animals turning on the treadmill indicate that this does, in fact, occur (Watson & Ritzmann, 1998b). Thus, the middle legs play an important role in turning the animal. They are also critical to changes in body attitude during climbing.

2.4. Climbing

In order to climb over a barrier, the cockroach first appears to measure the height of the object. It then pitches its body up and finally extends its legs forcefully to push it up and over the obstacle. We have very little information on how the insect measures the height of the object. However, we are confident that such a measurement is done, because in over half of the climbs that we observed, the front legs were placed precisely on top of the barrier without bumping into the side of the object. Reasonable sensory devices for making the measurement include the compound eyes and the antenna. They may in fact be acting in tandem to make the calculation.

In order to alter the attitude of the body in preparation for the climb, the middle legs are rotated so that the tibia is more perpendicular to the substrate (Figure 3) (Watson *et al.*, 1997). Once this is done, extension of the middle leg will pitch the animal up in preparation for the climbing movement. The rotation of the tibia occurs via a combination of movements at the body-coxa (BC) and

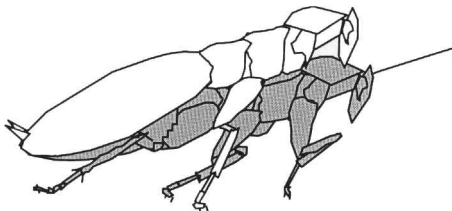


Figure 3. Diagram of a cockroach moving from a standing position (dark shading) to an elevated position (light shading) in preparation for climbing. The critical movement is a rotation of the middle leg that redirects the extension of that leg to lift the animal upward.

trochanter–femur (TF) joints. Both the TF joint and the BC joint of the middle leg are located at an angle, so that movement of the BC joint will rotate the leg segments distal to the joint. Because both of these joints are located proximally on the leg, relatively small movements at the BC joint can result in large rotations at the tibia and tarsus. The contraction of the BC joint rotates the coxa along its long axis. This movement is very different from the movement that occurs in the front and rear legs where contraction of that joint causes the coxa to rock forward, increasing the angle between the coxa and body as viewed from the side. In fact, during the climb the side view angle of the coxa and body does not change significantly from what occurs during walking. Nevertheless, the coxa rotation will swing the tibia to a more perpendicular position.

The movement of the TF joint is subtle. In fact, this joint was previously thought to be fused. However, we have found that a small flexion does occur and that such a flexion can contribute to the rotation of the tibia relative to the substrate. Indeed, when we did fuse the TF joint with staples or pins through the tendon, we found that the rotation of the tibia during climbing was reduced significantly, and the animal had a difficult time executing the climb.

Once the animal has reared up, it can then extend its rear legs forcefully to push it up and over the barrier (Watson *et al.*, 1997). It does this by activating Ds at a particularly high frequency to generate greater force and push the animal upward. We are currently performing experiments to test whether the increased activation is yet another example of a reflex adjustment initiated by the campaniform sensilla, which serve as strain detectors in the cuticle.

2.5. Summary of Biological Data

The biological data described above provides the essential parameters for design of the robot. By incorporating the insights that were gained in those experiments it was possible to create an agile hexapod vehicle with the potential to walk and run at various different speeds, turn and climb over barriers. We found that the most efficient way to incorporate these data into the design of the robot was to use a dynamic simulation tool that could utilize the digitized kinematic data to generate appropriate dynamic properties and then scale those factors up to the size of the actual robot.

3. Dynamic Model of *Blaberus discoidalis*

We developed a dynamic model of the *Blaberus* cockroach to help us understand the biological data and to aid in the design of the robot (Nelson, 1995; Nelson & Quinn, 1995). The model is based upon a quasi-coordinate formulation developed in the Bio-Robotics Lab that can be used to model accurately any legged animal or vehicle (Nelson & Quinn, 1996). The model has a total of 36 DOFs, three translations and three rotations of the body, and five actuated DOFs in each of its six legs.

Each cockroach leg has 10 segments and seven DOFs. Six of these segments are in the tarsus (foot) and are actuated by a single muscle group. We found that the majority of the locomotion data of interest could be modeled using the three major segments (coxa, femur and tibia) and five DOFs in each leg (Nelson & Quinn, 1995). In the interest of limiting actuation, this ignores for the time being the relatively small movement of the TF joint. We believe that we can capture that

action in climbing by making adjustments to the BC joint. The BC joint has three DOFs and the CF joint and FT joint are each modeled with one DOF.

The inputs to the simulation include the lengths and inertia of the leg segments and the body and joint angle trajectories from the behavioral studies discussed in the previous section. These joint angle trajectories were used as equilibrium point trajectories in the simulation. The joint torques are computed using a proportional-derivative control law:

$$\text{torque for a joint} = (\theta_{\text{actual}} - \theta_{\text{desired}})k + (d\theta_{\text{actual}}/dt - d\theta_{\text{desired}}/dt)c$$

where θ_{actual} is the actual angle, θ_{desired} is the desired angle, and k and c are constants.

The joint torques caused the model's legs to move and when they contacted the ground they caused the body to move. The foot-ground interaction was modeled using a spring in parallel with a viscous damper and slip was permitted using a Coulomb friction model. Two sets of walking data were used, one for a tripod gait and one for a slower gait. In both simulations, the model walked similarly to the animal.

The outputs from the simulation include the joint torques, the body motions, the ground reaction forces and the structural bending moments in the leg segments. The body motions of the model are not input and therefore are a good measure of the success of the simulation. Because the mechanical properties of the model are similar to the insect, the joint torques are good predictions of those used by the cockroach. This information is useful for biologists because joint torques are difficult to measure in a walking animal and can be related to EMG data. The ground reaction forces are also a measure of the success of the simulation. Our predicted ground reaction forces agree qualitatively with measured data (Full, 1993). The ground reaction forces and structural bending movements can also be used in robot design to choose materials and size the components.

4. A Robot based on Biological Observations

4.1. Mechanical Design of Robot III

We designed the robot to be 17 times larger than the animal to ease the robot's development and to make use of commercially available actuator technology (Bachmann *et al.*, 1997; Nelson *et al.*, 1997). It is convenient to construct and work with a robot that is desktop size, about 1–3 ft in length. It is also easier to visualize its motions and conduct locomotion studies. We chose a length of 30 inches because we wished to use commercial air cylinder actuators. For this robot size the actuators are readily available.

Pneumatic piston actuators were chosen because their power-to-weight ratio is much higher than standard DC motors and they offer the possibility of passive spring-like properties. It has been shown that the passive spring-like properties of muscles are important for efficient locomotion of animals (Alexander, 1988). Our previous robots, Robot I and Robot II (Beer *et al.*, 1997; Espenschied *et al.*, 1995; Quinn & Espenschied, 1993), used DC motors that are good for slow locomotion as observed in stick insects, but they are not energetic enough for the complex locomotion goals of this robot.

We wished to reduce the number of DOFs of each leg as much as possible to simplify further the robot design. The joint angle trajectory from the biological data for the modes of locomotion of interest showed that two of the 3 DOFs in

the BC joint in the rear leg exhibited small excursions. Furthermore, one DOF in the BC joint in the middle leg was found to move only slightly and could be eliminated (Nelson *et al.*, 1997). We also felt that one DOF in the body-coxa joint in the front leg could be eliminated even though all five DOFs of that leg showed significant excursions.

The dynamic model discussed in the previous section was scaled up 17 times in length and used to test the reduced DOF design: three DOFs in the rear legs, four DOFs each in the middle and front legs (Nelson *et al.*, 1997). The middle and rear legs functioned similarly with or without the eliminated DOFs for both walking gaits. However, the front legs did not reach forward as far with the four-DOF configuration. We could have changed the joint trajectory input to try to compensate for this or we could have returned to the five-DOF design.

The choice between these two strategies was influenced by our original goals. The goals of the robot include climbing and turning as well as walking. As discussed already, the animal propels itself forward with its rear legs, and this can be performed using the three-DOF configuration. The middle legs pitch the body for climbing and yaw the body for turning. The four-DOF configuration for the middle legs is sufficient for these functions. However, as described already, the cockroach uses its front legs as sensorimotor ‘arms’ as it reaches and climbs over barriers. This function requires these legs to be the most dexterous pair and for this reason we chose to design the robot’s front legs with five DOFs (Figure 4(B)).

The robot was designed to be energetic and mechanically robust (Bachmann *et al.*, 1997). Our dynamic simulation was used further as a design tool for sizing actuators and structural members. Each leg was designed to be capable of withstanding 1.5 times the robot’s weight in its most extended configuration because in simulation it was found that a ground reaction force could be that large. Also, structural bending loads were predicted for the case where the robot model was dropped from a height of 1 inch on to three legs. Predicted torques during simulated locomotion were used to size the pneumatic actuators.

The range of motion of each DOF is just as important as the number of DOFs in the legs. The desired range of motion for each DOF was determined from the biological data. Where possible the joint ranges of motion are 110% of the desired

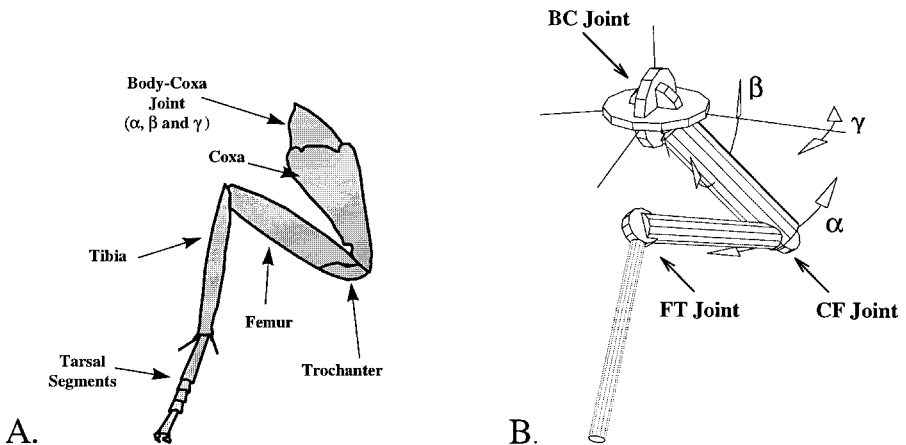


Figure 4. (A) Diagram of a cockroach front leg with segments labeled. (B) Schematic of front leg design showing five DOFs.

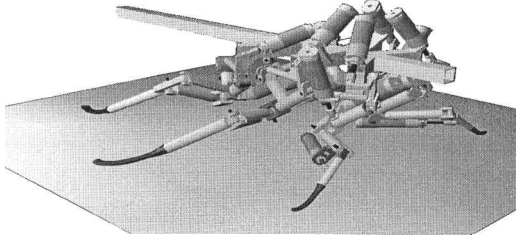


Figure 5. CAD model of Robot III.

minimum values. Actuator placement and actuator attachment points affected the mechanical limits of the joint range of motion. These further affected the actuator moment arms which determined the maximum joint torque possible for a given actuator size. In many cases two actuators were used for a given DOF to balance the force input and permit a larger range of motion of the joint. This design process was clearly iterative and computer-aided design (CAD) (Figure 5) was essential to visualize the leg configurations and determine mechanical interference and joint ranges of motion. Three prototype legs were constructed before the final leg designs were determined (Bachmann *et al.*, 1997).

4.2. Construction of Robot III's Physical Plant

The robot is 30 inches long and its structure, constructed mostly of aluminum, weighs 6.9 lb (Bachmann *et al.*, 1997) (Figure 6). Its leg segments are made of hollow aluminum tubes and its joints are fabricated of machined aluminum with roller bearings and hardened steel shafts. The tarsi are made of flexible plastic hoses clamped to the distal ends of the tibiae. The hose material was chosen for its stiffness and frictional characteristics. Coil springs are inserted inside the plastic tarsi of the middle and rear legs to increase the stiffness of these load-bearing legs. This construction models the passive stiffness of the animal's tarsi in a simplified manner and the friction is necessary to support horizontal loads in the stance legs.

The robot's total weight is 29.5 lb, including 36 double-acting air cylinders, 48 air valves (six blocks of eight valves), air hoses and wires. The air valves are located on the robot's 'abdomen' such that the fore-aft location of its center of mass is at the body-coxa joints of the rear legs as it is in the animal. A potentiometer is

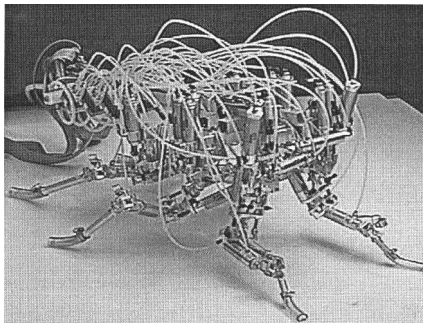


Figure 6. Robot III standing with a cockroach-like posture.

mounted at each joint to measure joint angles and a strain gage is mounted at the proximal end of each tibia to measure loading of the legs. These play the roles of chordotonal organs that monitor joint angle and campaniform sensilla that monitor cuticular strain in the animal (Zill, 1990).

The robot has 24 active DOFs. The minimum number of valves to control the robot is 48 three-way valves, one valve on each side of a double-acting air cylinder (or pair of cylinders). In this configuration the valve is always either pressurizing the one side of a cylinder or exhausting it and no air storage is possible. Unfortunately, the inability to store air eliminates the potentially useful property of passive stiffness.

The valves on the robot have a maximum frequency of about 200 Hz and are controlled using pulse-width modulation (PWM) at about 50 Hz. Before choosing pneumatic cylinders to actuate the robot, we tested the control system using a prototype leg with four DOFs and proportional control of individual joints (Nelson *et al.*, 1997). The system was demonstrated to have the necessary smoothness, path following and repeatability characteristics for locomotion.

The biological data show that the rear legs typically operate with the CF and FT joints coupled, in-phase, and moving through equal excursions (Figures 1 and 2). This provides the powerful piston-like motion that drives the animal forward. We designed the robot with three DOFs in its rear legs in case all three were later found to be important, but we left provisions for a linkage to be attached to reduce it to two DOFs. We have now installed a four-bar, parallel linkage mechanism on the rear legs and therefore have reduced the rear legs to two DOFs. This mechanism simplifies the control of the robot because it stiffly couples the CF and FT joints, thereby reducing wobble in the posterior of the robot.

At 30 inches in body length, the robot is 17 times larger than a typical adult *Blaberus* cockroach. Its leg segment lengths are also scaled to be 17 times larger than those in the animal. The rear legs are large and powerful and have two DOFs, the middle legs are smaller and have four DOFs and the front legs are smallest and have five DOFs.

4.3. Design of Robot III's Posture Controller

Posture control is the control of body motion in three translations and three orientations. Biological data from mammals suggest that robust posture control is essential for locomotion (Horak & Macpherson, 1995). Furthermore, these studies have shown that the higher centers of the nervous system are important for posture. Although decerebrate mammals are fully capable of moving their legs in a pattern reminiscent of walking, they cannot stand on their own. Thus, normal posture requires an interaction between local reflex circuits in the spinal cord and computational centers in the brain. These centers process various kinds of sensory data such as leg position, head orientation and visual cues and then act through the local circuits in the spinal cord to actively control posture in a task- and context-dependent fashion. Insects have a more sprawled leg design that could require less attention to active posture control. Nevertheless, our own preliminary observations indicate that even in insects, information from the brain is critical to maintaining balance during active behavior. A cockroach that has experienced a lesion of both neck connectives demonstrates grossly extended leg joints and has a strong tendency to overturn with any rapid movements. Although some of these problems are reversed with time, the animal does not recover its agility, even after a period of

almost 2 months. Our conclusion from these observations and those on mammals is that posture is more than local reflex interaction. It appears to be the orchestration and tuning of reflexes in lower regions of the central nervous system according to some desired behavior. Robot III's posture controller reflects these ideas (Nelson *et al.*, 1998; Nelson & Quinn, 1998): it is a centralized controller based on the virtual model approach (Pratt, 1995; Pratt *et al.* 1997; Raibert *et al.*, 1986).

There are no sensors on cockroaches to measure directly their total body position or orientation, but there are many proprioceptors that monitor joint angle, strain on the cuticle and position in extreme flexion. Total body posture can be calculated within the central nervous system from those proprioceptive measurements. In Robot III, body posture is also measured indirectly using proprioceptive data: from potentiometers on the stance legs. Even in humans, proprioceptive data are very important for posture control. Patients who have lost proprioceptive input to the brain have difficulty remaining upright, even though their vestibular system is functioning normally (Horak & Macpherson, 1995).

The input to the robot's posture controller is the desired body position and orientation. The desired force F (in the x , y and z directions) and moments M (about the x , y and z axes) on the body required to cause this motion are calculated based on the robot being modeled as a body attached to six springs, one for each of the body's six DOFs, for example:

$$F_i = K_i(\text{actual}_i - \text{desired}_i)$$

where actual_i is the actual body position in the i direction, desired_i is the desired body position in the i direction, and the subscript i denotes any of the three directions x , y or z .

The posture control problem then is one of assigning the load-bearing responsibilities to the stance legs such that their summation causes F and M to be exerted on the body. As the robot walks, the stance legs typically number from three to six. Therefore, the number of equations needed to solve this load distribution problem varies with the gait and the phase of the gait.

The problem is separated into a solution for the vertical force distribution (z direction) and a solution for the horizontal force distribution (x and y directions) (Nelson & Quinn, 1998). The coordinates are defined further in Figure 7. F and M are used to determine the desired center of pressure (COP) for the robot (Figure 7). Equations are developed that constrain the sum of the vertical forces from the stance legs to equal F_z and the COP to be positioned as desired. Typically, depending on the number of legs in the stance phase, there are not enough constraint equations to solve directly for the vertical force required from each stance leg. Therefore, in addition to the constraint equations, an optimization problem is solved that encourages an equal sharing of vertical load among the stance legs. Note that normally the legs will not share an equal vertical load because of the enforcement of the constraint equations.

Independent constraint equations based on satisfying F and M on the body are formed to solve for the horizontal forces. Again, the problem is typically under-constrained and an optimization is used in the solution for the horizontal forces that encourages minimization of the joint torques in each leg. This has been shown to cause horizontal ground reaction forces directed in toward the body. A force distribution similar to this has been measured in walking cockroaches (Full, 1993).

With this posture controller the robot stands and resists large disturbances. When pushed from the side repeatedly while standing, it appears to exhibit a

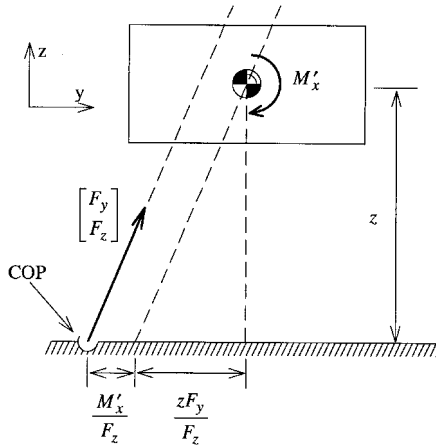


Figure 7. The desired center of pressure (COP) for the body can be found based upon the desired forces F and moments M . Note that z is the vertical direction, x is the heading direction and y is the lateral direction, which follows for a right-handed coordinate system.

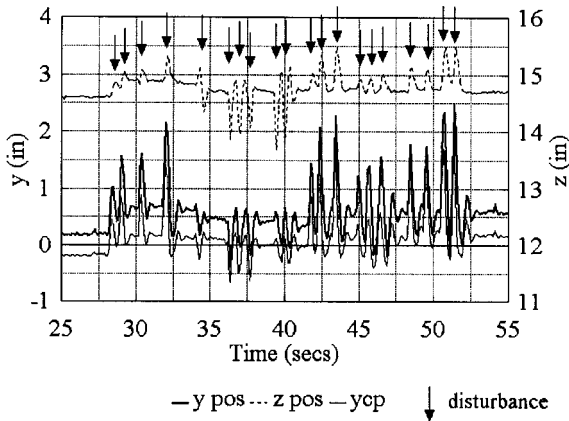


Figure 8. Robot III's posture controller rejects disturbances (reproduced from Nelson and Quinn (1998)). The arrows indicate when the disturbance forces were applied. $ypos$ and $zpos$ are the y and z components of the position of the body and ycp is the y component of the position of the center of pressure.

swaying reflex similar to that observed in animals (Figure 8). To demonstrate further the posture controller and to show the robot is powerful, Figure 9 shows Robot III performing push-ups while carrying a 30 lb weight (Bachmann *et al.*, 1997; Nelson & Quinn, 1998).

The posture controller forms part of a locomotion controller. When the commanded body position is moved forward, the stance legs push the body forward. For the robot to walk, a gait controller must be added to encourage stance legs to lift and enter their swing phases in a coordinated manner. Also, a controller must be added to cause the legs to swing forward and transition to stance.

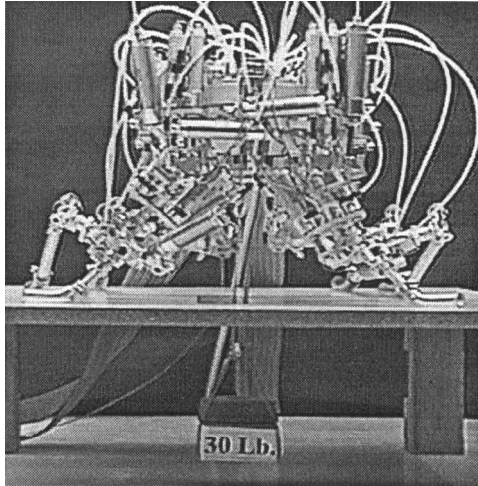


Figure 9. Robot III performing push-ups with a 30 lb payload.

5. Conclusions

We have constructed a robot based strongly on the kinematics and behavioral observations of cockroaches. Our strategy has been to use the animal's design and behavior as the default in the design and control of the robot rather than using the biological design only as inspiration to solve engineering problems. We resisted the urge to use a traditional engineering solution when the biological data suggested otherwise, even if it would appear easier. As a result, we have a robot that responds to disturbance in an animal-like way and, we believe, will locomote in an animal-like manner. An additional unforeseen payoff is that many of the problems that arise in controlling the robot lead to new understanding of the animal. These include the appreciation of the need for stiffening leg joints in anticipation of loading and the probable role of a sophisticated central control circuit that controls posture through interactions with local distributed circuits.

Robot III's leg designs capture remarkably well the DOFs, joint angle excursions and segment ratios that are necessary for walking and climbing in the animal. This design is both a blessing and a challenge. In contrast, other hexapod robots, including Robot II which was constructed by our group, have simpler leg designs (Beer *et al.*, 1997). Typically, they include fewer DOFs and all six legs are similar in construction. We believe that the leg designs for Robot III will ultimately make it behave in a more animal-like fashion, and this has been borne out in the posture control. However, controlling the front legs has proved challenging because of their five DOFs and relatively small inertia. A typical inverse kinematics approach such as that used in Robot II is difficult because of their redundancy. Even with these difficulties, there is benefit. The problems that we have encountered in controlling Robot III point to similar problems that animals face in controlling their legs, that if anything are even more complex. Thus, as a result of the close attention to biology in the design of this robot, the problems in control have led to insights in biology.

Although we are excited about the results of this project, we recognize that a detailed attention to biology is not necessary or desired in all Biorobotics projects. Depending on the ultimate goals of the project, a group might be more inclined to

use more traditional engineering methods and only look to biology for specific solutions. Indeed, in other projects that our group has undertaken, we have used this strategy. In deciding which strategy to take, a Biorobotics group must first define the ultimate goals of the project. The goals of Robot III dictated a more detailed use of biology.

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