Abstract

This paper describes the design and simulation of a cockroach-like hexapod robot which is under construction for the purpose of testing control principles which are being extracted from the cockroach. The cockroach was chosen because of its remarkable running and climbing capabilities and because much is known about its biomechanics and control. The robot is designed with five, four, and three degrees of freedom in the front, middle and rear legs, respectively, to permit it to mimic the different functions of cockroach legs. Pneumatic cylinders actuate each joint and provide opposing muscle-like forces to actuate the joints. Pulse-width modulation controls the actuators with the necessary smoothness and precision. A dynamic simulation has been developed to predict loads on the structure and the required joint torques.

Introduction

For some time now, roboticists have been aware of the reservoir of insight available from a well guided study of existing biological systems. Locomotion, and in particular walking, have received a significant portion of this attention. An effective mobile robot should possess the ability to operate successfully in a complex, dynamic environment. Indeed, walking robots exemplify the need for this ability, as many discussions about locomotion have stressed, and studies of locomotion in nature strongly suggest\textsuperscript{1,2}.

Previous work has shown that the performance of a robot can benefit greatly when biological principles are incorporated into its mechanical design. Raibert and colleagues constructed highly successful monopedal, bipedal and quadrupedal hopping and running robots by incorporating biologically-inspired dynamics into their designs\textsuperscript{3}. Researchers at the University of Illinois, Urbana-Champaign constructed a pneumatically actuated hexapod robot with inspiration from cockroach biomechanics\textsuperscript{4}. Each leg of their robot has three degrees of freedom. Binnard, also inspired by the biomechanics of the cockroach, built a hexapod robot, named Boadicea, powered by custom-designed pneumatic cylinders\textsuperscript{5}. This robot has two degrees of freedom (DOF) in the front leg and three DOF in the middle and rear legs. Pfeiffer and colleagues built an autonomous robot modeled closely after the stick insect and implemented a controller which was based on the mechanisms thought to be responsible for its leg coordination\textsuperscript{6}. This robot has three DOF per leg and is actuated by DC motors.

A research team at Case Western Reserve University has developed and built two hexapod robots based on biological inspiration. The first robot, R-I, was constructed to test, in hardware, a previously developed neural network locomotion controller\textsuperscript{7}. This robot, possessing six legs, each with two DOF, walked in a continuum of insect-like gaits on a flat surface\textsuperscript{8}. Another controller based on the mechanisms thought to be responsible for the coordination of the legs in the stick-insect, was also developed and implemented in R-I with similar results.

The second hexapod robot, R-II, was designed to be mechanically similar to the stick insect. It has six legs, each with three revolute DOF. A turning strategy and insect-inspired reflexes were incorporated into the stick
insect controller previously designed for R-I. The capabilities of R-II are diverse: it walks with a continuum of insect-like gaits; turns, yaws in place, walks forward, backward and sideways; walks on uneven terrain including slatted surfaces\(^9,10\).

Continuing this research effort, the biologically-inspired robotics group at CWRU has undertaken the construction of a third hexapod robot (R-III). The cockroach *Blaberus discoidalis* (Figure 1), is being used as a model for its design. Cockroaches in general possess many unique locomotion capabilities. The foremost is their incredible dexterity, demonstrated in both extremel rapid running (the American cockroach, *American periplenita*, is considered among the fastest land animals in the world, using a body length velocity metric), and the ease and agility with which they negotiate rough terrain. Researchers at CWRU and elsewhere have studied *Blaberus discoidalis* extensively. Many significant insights into cockroach biomechanics and locomotion control have been gained\(^11,12\).

Towards this end, we developed a detailed dynamic simulation of *Blaberus* cockroach locomotion\(^13\). This 36 DOF model contains six 5 DOF legs, each composed of coxal, femural, and tibial segments, supporting a free translating and rotating body (Figure 2). A simplified cockroach leg model was developed with three revolute DOF at the body-coxa (BC) joint, and one DOF each at the coxa-femur (CF) and femur-tibia (FT) joints. The input to the simulation included the mass and kinematic properties of the animal. Joint motion data from high speed video of walking and running cockroaches were input to the simulation as desired values for PD controllers at the joints. Output from the simulation included joint torques, ground reactions, and overall body motion. Information and insight gained from these simulation studies has provided the basis for the design of our new cockroach-like robot.

This simulation technique is also being used to gain more information about how cockroaches climb barriers and perform turns. A terrain model has been incorporated into our dynamic simulator with great success. This is being used to design R-III and will be used to develop its controller in simulation while the hardware is being fabricated.

**Design**

Unlike R-II, which has six identical legs, the functions of the front, middle and rear legs of the cockroach are very different, and the design of R-III mirrors this. The rear legs of the cockroach are large and powerful, but use a simple “piston-like” motion to drive the animal forward. To illustrate this, it has been shown that when running rapidly, the American cockroach can sprint in a bipedal gait on its rear legs\(^3\). The middle legs, with feet laterally below the animal’s center of mass (CM), are used for supporting the body, turning\(^11\), and lifting the body to climb over a barrier. The dexterous front legs appear to have several complex functions outside normal walking, the most interesting of which, for our robot, involve sensory feedback. Thus, using the cockroach as a model for a walking robot, one can approach many of the interesting and fruitful aspects of walking robot research, in particular, speed and navigation, terrain negotiation, and sensing.

Figure 3 shows an approximate solid model CAD representation of R-III. R-III will have 24 DOF. Based upon a uniform length scale, its length of 30 inches is approximately 17 times larger than the animal. Like the cockroach, each leg is composed of three moveable segments, proximal to distal: coxa, femur, and tibia with a flexible tarsus (foot). Because of the differing functions of the cockroach legs, we have designed the robot with five DOF in the front legs, four DOF in the middle legs, and three DOF in the rear legs. This is in contrast to o-adicea, which has two, three, and three DOF in the front, middle and rear legs, respectively\(^5\).

The robot frame is made from 6063-T52 aluminum alloy, and the legs are made of 6061 and 7075 alloys with T6 or T6511 temper designation. These alloys have a high strength to weight ratio and are easily machined and welded. Off-the-shelf double acting pneumatic cylinders simulate opposing muscle pairs actuating revolute joints. Each joint assembly is a hardened steel shaft running in full complement needle roller bearings, to minimize torque and wear. A single-turn wire-wound potentiometer mounted at each DOF supplies joint angle feedback. Two 3-way solenoid valves control airflow into each dual-acting cylinder.

The individual leg segments resemble animal skeleton, minimized in the middle, but reinforced at the ends, to withstand applied loads and stress concentration. Figure 4 shows a typical femoral leg segment, including the tibia actuator, and part of both the tibia and...
coxa. In this case, the femur is composed of the cylinders themselves. The cylinders insert into solid, machined joints at each end of the femur. The proximal joint includes the CF joint shaft and a coxal insert, while the distal joint includes the bearing housing for the FT joint and femoral insert. Each joint is driven as a four bar mechanism, with the proximal segment and pneumatic cylinder housing, cylinder rod, transmission link, and distal leg segment acting as the ground, driving, transmission, and driven links, respectively.

Reference data for the kinematic design and strength analysis were obtained from our previous studies. Data included: leg segment lengths with respect to overall body length, leg attachment locations with respect to center of mass and overall body length, approximate joint excursions for tripod and slow metachronal gaits, and approximate ground reaction forces as a function of these two gaits. The many DOF of the cockroach leg have been condensed into a nontrivial five DOF model. Figure 5 shows a left leg with body-fixed reference frames, all joint angles being zero. The five DOF are three Euler rotations at the BC joint, in a z (γ_C), y (β_C), x (α_C) sequence, a rotation about the z axis of the femur (γ_F), and a final rotation about the z axis of the tibia (γ_T).

With a knowledge of cylinder and valve weights, a target robot weight (W_r) of 25 lb. was assumed, along with a desired percentage of actuator weight (W_a) of approximately 60%. Currently, W_i is about 21 lb., and W_a / W_r is about 0.7.

For the strength analysis, the leg model was configured in its poorest load bearing configuration, in a horizontal plane, with a vertical ground reaction force of 150% W_r. Using this worst case scenario of maximum moment arms under normal excursions, joint structures were designed and cylinders were chosen. To determine tubing size, the maximum normal stress due to bending and maximum shear stress due to torsion were superimposed, and a factor of safety of 1.25 was used. These designs have been further refined using the dynamic simulation of the robot. The simulation provides required joint torques as well as structural constraint moments for any static or dynamic loading condition.

The sensory and problem solving function of the front leg required that it have maximum flexibility, thus retaining all five DOF. One problem that occurred with this design was that the cylinder actuating the tibia struck the ground during walking. To overcome this clearance problem, the actuator cylinders will be used as the structure of the femur (Figure 4). Also, the R-III simulation is being utilized to optimize cylinder sizes throughout the robot.

While similar to the front leg, the middle leg requires less dexterity. Therefore the γ_C DOF is removed. This leg will be mounted at a fixed γ_C angle, which will be manually adjustable for optimization purposes. However, the α_C DOF is present so that the middle leg can lift
the body more effectively. In the rear leg, the $\alpha_c$ DOF is replaced by a rigid structure.

Three dimensional solid modeling of the entire robot showed the need for other adjustments. There were several clearance problems at the robot centerline, caused by femur actuators of contralateral legs. To overcome this, the leg attachment points of each side were moved out from the centerline by a small amount. This corresponds to less than a 10% change in overall footfall width. Also, on consecutive legs on the same side of the body, $\alpha_c$ joint mechanisms could interfere. This problem was solved by moving the front legs forward slightly and the rear legs back, with respect to the desired center of mass. This again amounts to less than a 10% change in average footfall distance between the front and rear legs. By carefully locating the relatively massive servo valves on the robot’s “abdomen”, the robot’s c.m. will be located on its body in the same relative location as that of the cockroach. This helps to distribute weight equally among the legs of the robot.

Prototype Leg Hardware and Control

A prototype four DOF front leg, shown in Figure 6, was constructed to test the hardware design and control mechanisms. The leg structure is very similar to the design intended for the robot. The joints are actuated using off-the-shelf, pneumatic, double acting cylinders. Each cylinder acts as both the flexor and the extensor muscles of the animal, and is controlled by a pair of three-way solenoid valves. The valves are available as a single unit comprising eight separate three-way valves for a total weight of 10.5oz.

Pulse width modulation (PWM) is being used for flow control of the solenoid valves. The valves have a nominal maximum frequency of 200Hz, and are being operated at approximately 50Hz. This rate is fast enough to eliminate large vibration, yet it is well within the operating range of the valve. Both three-way valves controlling a single cylinder are pulsed in phase to further eliminate vibration. The pulse lengths for a valve pair are inversely varied to create a pressure differential in the cylinder. An optically isolated digital I/O PC board commands the valves.

Feedback is supplied by using rotary potentiometers (POTs). Each POT measures the relative joint angle between adjacent leg segments. The POTs are sampled through a 12-bit A/D board.

The joint control law is a form of force control in which each side of the cylinder acts as an opposing spring. Motion is achieved by creating a pressure differential, itself produced by varying the valve duty on each side of the cylinder about some nominal value. Proportional control is implemented with separate, software-controllable, proportional gains for each cylinder. In addition, the nominal median valve duty for each cylinder is also controllable. This variable is effectively a viscous dampening term since it controls the average amount of time that the valve orifice is open to the exhaust. The control law has the form,

$$F = k_p (x_{desired} - x_{actual}) + c \dot{x}$$

where $k_p$ is the proportional gain and $c$ is the damping constant.

Using this model and position command control, we were able to test the leg’s ability to accurately and fluidly create desired motion. Code was also written so that the leg could be manually guided or taught a specific, “desired” motion and then the controller could be used to attempt to cause the leg to replay that motion. The results were encouraging.

During one test, the leg was commanded to perform a sinusoid-like motion, and both the commanded position and the actual position, as measured by the POTs, were recorded. A graph of the result for one joint is shown in Figure 7. As is expected with proportional control, the actual data follows the desired with an offset error. The same test was also performed with a 1Kg mass attached to the tibia. Similar results were obtained.

In another experiment, a pen was attached to the leg’s tarsus, and the operator drew a path on a piece of paper and then commanded the leg to repeat the path. One sample is shown in Figure 8. The top path was created by guiding the robot leg with pen attached, and the bottom path was drawn only through robotic control. Again, there is a bias that is inherent in proportional control systems, but because the leg was also used to control...
address the position command file, the errors due to mechanical backlash are amplified. Figure 8 does show that the leg is able to precisely recreate motion with minimal vibratory effects.

A similar experiment commanded the leg to create a path and then repeat the path on the same paper. The result is shown in Figure 9. As can be seen from the figure, we obtained excellent repeatability. This bodes well for PWM control of pneumatic valves as an accurate and easily controllable means of motion control for legged robots.

Simulation

Using the same simulation technique formulated for the cockroach, and a crab-like robot designed by K-T, Inc., a simulation of R-III has been developed. The technique has been significantly improved in this case, utilizing many simplifications to increase execution speed four to five hundred percent. In some cases, real-time simulation may be possible, although not a significant goal for this project.

Initial simulation results show that resting torques required for a standing prototype robot are less then ten percent of the specified designed capability. Although this may appear attractive, previous simulation studies of a running cockroach show that over 150 percent of body weight may be sustained by one leg during a tripod gait. To compensate, the simulation will be used to investigate control algorithms which utilize energy storage and transfer during more dynamic gaits. The compressibility properties inherent in a pneumatic actuation system will be a particular focus, in an effort to analogize varying joint stiffnesses in the animal due to coactivation of antagonists.

Simulation results also indicate that the prototype robot design is capable of producing sufficient torques for a fast metachronal gait. Peak torques occur at the most inboard joint of the rear leg, which is expected based upon the average posterior position of the CM behind all leg attachment points, and the size and pose of the rear legs in relation to the CM.

Figure 10 shows graphical output from the simulation. The lower figure shows ground reactions on each foot that is in contact with the ground. As in the cockroach and our previous legged vehicles, leg contributions to locomotion are preserved in the prototype robot design. The front legs primarily provide braking forces in the direction of travel, while the hind legs supply accelerating forces. Based on control parameters, the middle leg

Figure 7: Testing joint control on the prototype leg.

Figure 8: Testing path following capabilities.

Figure 9: Testing repeatability of controller.

Figure 10: Simulation of Robot III.
can provide various degrees of both braking and accelerating forces throughout its stance cycle.

The leg designs are being tested in simulation because the front leg must possess a significant degree of flexibility, further simulation results have suggested competing designs. A number of separate leg designs can be tested in simulation to investigate their ability to reach, climb, and turn. For instance, the \( \alpha \) DOF was added to the middle leg, to be constructed much like the prototype leg in Figure 6, so that it can lift the body more effectively for walking over obstacles.

Conclusions

This paper describes the design and simulation of a pneumatically actuated hexapod robot. The Blaberus cockroach was chosen as a model for the robot based upon the multifaceted capabilities that it prescribes for the robot: speed, agility, and integration of sensory information. The robot has been designed with five, four, and three degrees of freedom in the front, middle, and rear legs, respectively. This configuration was chosen in order to permit the legs to mimic the cockroach leg functions for locomotion, turning and climbing. A dynamic simulation has been developed as a design tool for the robot’s mechanics and its controller. Preliminary results show that the robot’s power to weight ratio should permit the robot to locomote quickly and climb over rough terrain. The PWM joint controller has been shown to be capable of moving the joints with the necessary smoothness and precision.

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