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Design of a Cricket Microrobot

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Abstract

Our goal is to develop an autonomous robot that will fit within a two-inch cube and will locomote by walking and jumping. The robot will be based on the kinematics of a cricket. It will be actuated by braided pneumatic actuators with compressed air provided by an onboard compressor. The air will be distributed by an array of actuated MEMS valves. A neural network will control the robot and it will be implemented in an analog VLSI circuit. The joint angles will be measured using MEMS joint angle sensors that are based on biological sensors studied in the cricket and other insects.

1 Introduction

The Biorobotics lab at CWRU has been building biologically inspired robots for the last nine years. We work in concert with biologists from CWRU and Marshall University. The cooperative work has been good for both groups. We have gained valuable insight into biological systems. The biologists have been able to use our engineering research to help evaluate their findings. We have built three generations of robots using biological principals. Each new robot has been shown to be progressively more capable. Robot I demonstrated the flexibility of a neural network controller [14]. Robot II used legs that were more biologically inspired and, more importantly, its controller incorporated reflexes observed in insects. This made it able to deal with rough terrain and obstacles [8]. Robot III, still in development, is a pneumatically actuated robot where robots I & II where gear motor actuated [2]. Robot III is modeled closely after a cockroach and has so far been shown to have exceptional power and robust posture control and promises to be an agile robot [11], [12]. With the experience in design and construction of insect like robots we hope to miniaturize what we have learned and make a microrobot based upon a cricket.

In this paper we describe the design of an autonomous microrobot that will fit within a two-inch cube and will locomote by walking and jumping. These robots will be able to carry small sensors and become dormant to extend their useable lifetime. Their small size allows one human to carry several robots and allows relatively small vehicles to deploy large groups of robots in swarms. Since one of the possible missions of this robot will be surveillance, the small size can also help them hide. This increases their survivability in a hostile environment where their presence is not wanted and detection will terminate their mission.

The small size requirement increases the difficulty of the project. Manufacturing and assembly of the many custom components is the biggest problem. Finding a small, light, power source is also a challenge. We have to design and build actuators, sensors, and control systems that will fit in a small package. The small size also makes locomotion more challenging, and the microrobot will have to be able to maneuver in a variety of terrains. These issues will be discussed in the next sections.

2 Conceptual Design

We have based our design upon the cricket [10]. This insect possesses many traits that we would like the microrobot to have. For example, the cricket has the ability to both walk and jump and can traverse a variety of difficult terrains. It can use its ability to jump to navigate terrain with features much larger than itself.

The robot will have six legs that will be similar in function to that of the cricket's legs (Figure 1). However, the robot's legs will be kinematically less complex than those of the cricket to simplify their design. The two large powerful rear legs have just two degrees of freedom (DOF), but function similar to the cricket's rear legs in walking and jumping [10]. The front two pairs of legs of the cricket are much smaller but are more agile and have been designed with three DOF. This leg arrangement will

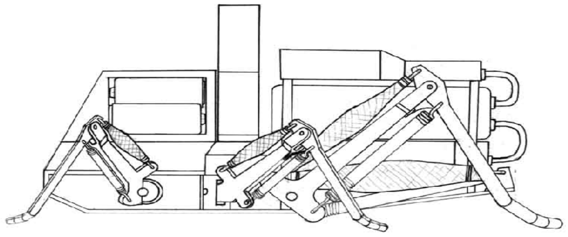

Figure 1: Conceptual design of the microrobot

permit the microrobot to have the two desired modes of locomotion. One will be walking used for slower locomotion and maneuvering, which will allow the robot to navigate to specific locations and orientations. The microrobot will also have jump capability, for moving over larger obstacles and traveling more quickly with less energy.

The robot will be actuated with one single-acting, tension actuator per joint. We will use springs as passive tension members to oppose them. This strategy reduces the number of actuators and valves by half. The actuators are placed so that the torque they generate is used during stance and the springs are used during swing.

The power source for the microrobot will be several lithium batteries. The batteries power a Smoovy™ motor that drives a compressor that will, in turn, supply compressed air for the leg actuators. The batteries have been shown to drive the Smoovy™ motor on an autonomous hopping robot continuously for 45 minutes [16].

The controller will be a continuous-time recurrent neural network in an analog VLSI package [3], [4]. This controller will switch an array of two-way MEMS valves that will distribute the compressed air to the actuators. Feedback to the controller will include joint angle sensing at each joint. The joint angle sensors are another MEMS device that is based on biological sensors studied in the cricket and other insects, and are being developed at Carnegie Mellon University [7]. The robot must also have force sensing or an accelerometer to determine its orientation with respect to the ground after each jump. Force sensing is known to be essential for insects [17].

We used scaling to estimate the weight and power needs of the cricket microrobot. Our 30 inch long cockroach robot, RIII, is driven by pneumatic actuators. The length scale factor L is 15. The mass scales by the cube of L. The acceleration of gravity is the same for both robots. Thus, in scaling, acceleration is assumed a constant. These relationships provide the following estimates for the 2 inch long cricket robot: It should weigh about 0.009 LB, require 0.0034 CFM of 7 PSI air and 0.076 Watts of power. Because RIII is not autonomous, the autonomous microrobot will require more on-board hardware and will weigh more than this estimate. Also, RIII can not jump far and the microrobot will require more pressure than this estimate to jump, but jumping will be discontinuous and will require less air flow. Furthermore, the MEMS valves may not be able to cycle at the high scaled rate for walking and this would reduce the walking speed and the required air flow.

3 Actuators

Braided pneumatic actuators, also known as McKibben artificial muscles, will drive the joints of the microrobot. They have gross force and length properties similar to muscle and provide joint elasticity that is known to be important for animal locomotion [1]. They consist of an expandable bladder inside a tubular mesh made of relatively inelastic fibers [6]. With this arrangement (figures 2 & 3) when the bladder is inflated the only way for the volume of the actuator to increase is for the diameter of the mesh to increase. The inelastic fiber in the mesh causes the actuator to contract along its axis as its diameter is increased [5]. Large versions of these actuators are commercially available.

Figure 3: Actuator inflated

The construction of actuators small enough for our microrobot requires that all the parts be custom made. The actuators measure approximately 0.875-1.125 inches long with an inner diameter of about 0.050 inch and the outer diameter is about 0.125 inch when deflated. The latex bladder was made by hand because, commercial latex tubing makers were unable to make tubing with both a small enough inner diameter and a thin enough wall.

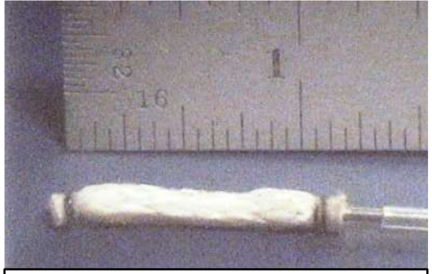

Figure 2: Actuator uniflated

The first step in manufacturing the actuators was to select the proper diameter wire to obtain the desired inner diameter of the bladder. Music wire of several diameters was tried to find the best diameter. The wire used to make the actuators for the rear leg was 0.047-inch diameter and was polished. Then the wire was dipped in uncured latex rubber. By varying the number of times the wire was dipped and the time between dips, we were able to vary the thickness of the latex tubing. After several tests, it was determined that two coats with about 15 minutes between coats gave us consistent wall thickness of about 0.010-0.013 inches. The tubing was then powdered internally with talcum powder to help keep the latex from sticking to itself. The finished tubing was then sent to the Philadelphia College of Textiles and Science to have the mesh braided. The mesh was woven from sixteen bundles of a micro-denier polyester fiber, with eight bundles wound clockwise (CW) and eight counter clockwise (CCW). The fiber bundles were woven over two bundles then under two with the adjacent bundle offset by one bundle. This mesh is woven directly over the latex tubing with a wire reinserted to stiffen the tubing. This finished assembly is about 5-6 inches long. The angle between the CW and CCW fibers is critical. The equilibrium angle for the mesh when inflated is about 54.6 degrees with the axis of the actuator. To have contraction, the starting angle has to be smaller. The smaller the initial angle, the more contraction occurs when inflated. The drawback to this is that if the angle is too small there will be problems with mesh stability. After several tries we found a good angle of between 20 and 25 degrees.

One major problem with the actuators is their tendency to have a bladder aneurysm due to mesh instability. This occurs when a small distortion in the mesh allows a bulge in the bladder to rupture through it. This usually results in the bladder destroying itself. Coating the outside of the mesh at the ends of the actuators helps stabilize the mesh, reducing the chance of a rupture. The drawback to this is that the more length of fibers coated the more the contraction of the actuators is restricted. Therefore, a balance must be found between stable actuators and efficient actuators.

Once the actuator is cut to length, one end is crimped shut with a short piece of wire, and the other end is clamped around a small piece of stainless steel tubing. The stainless steel tubing allows for the attachment of the actuator to the air source by a piece of flexible Teflon tubing. In the rear leg, the clamps are screwed into the skeleton of the leg at the actuator's origin. This arrangement keeps the bulkier, fitting end of the actuator inboard on the leg and shortens the length of Teflon tubing needed. The other end is connected to the insertion point for the actuator.

4 Compressor

An onboard air compressor will power the braided pneumatic actuators. The design of the compressor is a gear motor driving a crank and rocker mechanism to reciprocate a piston in a cylinder (See Figure 4). The gear motor is a five-millimeter Smoovy motor with a two-stage planetary transmission with a final transmission ratio of 25:1. Smoovys are three pole brushless DC stepper motors capable of 100,000 rpm, but the transmission has an input limitation of 15,000 rpm. When running the motor at 15,000 rpm the output of the transmission is 600 rpm thus running the compressor at 10 Hz.

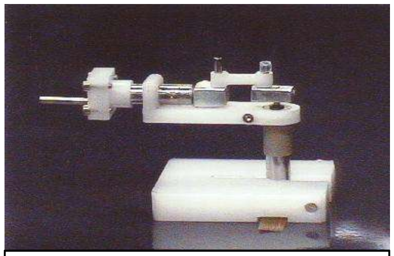
Figure 4: Micro Compressor

The compressor has a 5/32 inch bore piston with a stroke length of 3/16 inch. The pump is designed to operate at 35 psi max pressure, but this specification has not been attained yet. We are still working to improve the two check valves that control the flow of air through the compressor. The check valves are implemented in one MEMS device that allow outside air into the cylinder on the return stroke and out to the reservoir on the compression stroke. The dimension of one die is 5 mm × 8.75 mm × 400 µm. It is fabricated with KOH bulk etching to make the valve seat and with DRIE to etch the orifice and spring. The check valve is assembled with two similar dies back to back, each having an orifice and a spring. There is a valve seat 100 µm high around the orifice on which the spring sits. The spring works as a flap to block the flow in one direction and to let it flow in the other direction. At present the pump is able to produce a pressure of about 13 psi.

The pump's frame and push arm is machined from Delrin. The axles are made from stainless steel tubing. The other parts are machined from aluminum. The piston and cylinder walls are a modification of a 5/32 bore ¼ inch stroke Clippard air cylinder. The piston uses a Viton cupped ring seal and has a helper spring in the cylinder. This spring smooths the torque curve necessary to drive the compressor. If the spring were not in place the torque needed on the compression stroke would be too high for the motor, and the return stroke would require very little torque. By putting the spring in place we lessen the torque required on the compression stroke by storing some energy in the spring on the return stroke.

5 Leg Simulation

A simulation of one rear leg of the robot was developed. We chose to study the rear leg first, because we expected it to be the simplest to model. The kinematics of the cricket leg were extensively studied and we came to the conclusion that we could simplify the leg to include just two degrees of freedom [10]

The cricket's leg has about six degrees of freedom and its four major segments are the coxa, femur, tibia and tarsus. The coxa is most proximal to the body and has a three-degree of freedom joint at the body. The coxa connects to the femur and has two degrees of freedom. The femur then connects to the tibia with a single DOF joint. The last segment is the tarsus, which is the cricket's equivalent of a foot.

Figure 6: Demo Leg With Inflated Actuators

To meet the goals of our robot with minimum complexity, we were able to simplify the rear leg into two segments with two DOF. The number of segments could be reduced because the coxa in the cricket is an extremely short segment allowing us to approximate the femur as being joined directly to the body. In addition, the tibia and tarsus segments were combined, because the tarsus is a flexible assembly of short segments that will be emulated by using very flexible wire fixed to the end of the tibia.

High-speed video analysis of the cricket walking and jumping led to a reduction in the number of DOF [10]. The animal's leg's were painted with points at each joint and then this data was digitized into two orthogonal planes. From this data the 3D kinematics of the legs was determined. We were then able to take the vectors representing the legs segments and determine the axis of rotation at each digitized time step. After this analysis, we showed that the cricket's rear leg walking and jumping motions could be emulated with only two DOF. During the two phases of walking, stance and swing, the leg rotated about a nearly fixed axis. There is a deviation from this fixed axis during the brief transition period between stance and swing, but this will not affect the motion of the robot. Even more fortunate was that the cricket's leg was found to be nearly planar. The two joints needed to emulate the motion were only a few degrees askew to each other. This made the simulation of the leg equivalent to a double pendulum problem.

After the equations of motion of the leg were coded we added simple models of the springs and braided pneumatic actuators to generate the torque at the joints. There was also a very simple model of airflow through the actuators and valves. This simulation was then used to help train a neural network controller.

6 Controller

Two controllers were developed for the rear leg of the robot, one based upon a simple feed-forward design, and the other using a continuous-time recurrent neural network (CTRNN). The feed-forward controller, programmed on a PIC, sends a sequence of brief pulses to the actuator valves to open and close them. It ignores feedback from the joint-angle sensors, and maintains its operating range over time by backing the leg into the natural stopping position created by the zero-pressure state of the actuators.

The CTRNN-based controller was developed using a genetic algorithm to search the multidimensional space formed by the neuron parameters, as these parameters are difficult to calculate by hand. A genetic algorithm uses a fitness-function heuristic to guide the search into regions of the search space which solve the problem most effectively. The fitness function used in this case required each joint to achieve a particular position, at the extreme of its desired range of motion, at a particular time. The fitness score awarded was higher depending upon how close to the desired time the joint reached the desired position. After the joint reached this extreme of motion, the desired point was changed to the opposite extreme, and additional fitness was awarded for reaching this position in the desired time. Once the evaluation period had expired, a final fitness was added depending on the joint's proximity to the most recent desired point. This function directed the neural nets first to develop an oscillatory pattern and then to adjust the frequency of oscillation to the desired leg step frequency.

The architecture of the neural network involved two sets of two neurons each, one controlling the coxa-femur joint, and the other controlling the femur-tibia joint. Each neuron had a connection to the other neuron in its pair as well as to itself; in addition, one neuron of each pair received the output for that joint's angle sensor, and the pair's other neuron delivered the encoded output to the actuators. This architecture permits simple oscillators to be evolved for controlling the periodic motion of the leg.

The output encoding for the neural net was designed to permit the selection of three actuator valve states – inlet open, outlet open, and both closed with one output neuron. This was achieved by setting two thresholds on the signal generated by the output neuron. These neurons used the sigmoid function, which always ranges between zero and unity, to calculate their outputs. The outlet threshold was set at 0.2, opening the outlet valve at levels below this threshold, and the inlet threshold was set at 0.8. Any signals between these two thresholds caused both valves to remain closed.

7 Controller Hardware

The CTRNN control scheme used in simulation was a closed loop controller, which consisted of a prescribed, and a feedback portion. The feedback portion sensed the leg position using a feedback signal and adjusted the stimulus to the leg according to the desired leg position at that time. 100ms pulses delivered to the inlet and outlet valves governed the control. The feedback adjusted the cumulative width of these pulses. The base width of 100ms was chosen based on the simulation.

The analog VLSI hardware is not ready for implementation. Therefore we used a PIC for a demonstration of the rear leg of the robot. The primary requirements for a controller were analog input capabilities for the feedback signal, analog to digital converters, and reprogrammability for ease of code development. The PIC16C77 was a desirable compromise in terms of features, price and availability. The EEPROM 40-pin DIP version was programmed for the implementation of the control scheme described above. We scheduled a timer interrupt to be generated every 100ms. During each interrupt cycle the controller would either read its analog inputs or adjust its outputs, or follow a prescribed behavior.

Once the physical leg was built, we debugged the control algorithm in hardware. To simplify debugging, we began testing the controller in the absence of feedback signals. One of the first observations was that 100ms base pulse width was unsuitable for the system. This can be attributed to the fact that the parameters of the actual system were different from the model used for simulations. As a result, the motion of the leg was spasmodic. The outlet valves were venting too much air during their initial pulses, resulting in all of the motion occurring immediately as opposed to being uniformly distributed over the predetermined time for that motion.

A larger number of shorter pulses was better suited in providing a continuous walking motion. We decreased the base pulse down to the response time of the outlet valves (6ms), yielding a smoother more continuous leg motion. Our observations in the absence of feedback indicated that the system was able to successfully repeat the desired cyclical walking motion with no loading on the leg. Hence we decided to run the system open-loop for a demonstration of the leg.

Besides demonstrating walking motions of the leg similar to cricket, we also wanted to demonstrate kicking motions of the leg. We created a kick trajectory simply by commanding large discrete pulses to the femur tibia valves. We scheduled a wide pulse to the inlet valve followed by a wide pulse to the outlet valve. To obtain the desired kick trajectory we only needed to fine-tune the width of these pulses. In this case, we programmed the PIC with a base width on the order of 16 ms. The inlet valve pulse was approximately 1.5s while the outlet valve pulse was 0.5s.

8 MEMS Valves

The robot will have 16 active degrees of freedom and will need 32 valves to control the 16 McKibben actuators. For this purpose, we are developing a fully micromachined, normally-closed microvalve which consists of a spring, a patterned Titanium-Nickel (TiNi) shape memory alloy (SMA) actuator, and an orifice die, all of them made from silicon. The size of each die is 7.5 mm × 7.5 mm × 500 μm. It is designed for gas (air) flow of 6 cm^3/min at 35 psi (240 kPa) with a power consumption of 150 mW. The spring is fabricated by deep reactive ion etching (DRIE) and the orifice is fabricated using bulk wet etching with KOH. The actuator is wet etched followed by TiNi patterning and plasma dry etching to release the TiNi thin film. The actuation work density of TiNi thin films is as high as 5×10^7 J/m^3, which is typically two orders of magnitude higher than other actuation schemes.

9 Test Results

In September the prototype leg and compressor were demonstrated at a DARPA Distributed Robotics Meeting, held in the Quantico US Marine Corps Base in September, 1999. At the demo, we ran the leg through a series of tests. The first was a simple joint excursion test in which we ran the leg through a walking motion and compared the joint angles to that measured on the actual animal. The leg repeatedly stayed within ten percent of the animal's joint flexion, extension, and excursion. At the demo the leg was cycled over a hundred times during which it met this criteria.

The next test was a foot-fall pattern test. The leg was mounted in an orientation similar to that of the animal and a camera was placed so it could look from the bottom up at the leg if the leg was supporting weight. The leg was then cycled like it was walking, and the path the leg traced was then measured against a scaled path from the animal. The leg was also able to do this within ten percent. These first two tests demonstrate that the two DOF rear leg design is sufficient for walking.

The last test demonstrated the jumping power of the leg. This test put the leg in a position to kick a large paper clip having a mass of 1.2 grams straight up. The height was our metric. The leg in a trial of twenty kicks, averaged a height of 4.61 inches with a max of 5.25 inches. Although the leg's kinematics are sufficient for kicking, this kicking power must be greatly increased to propel the robot a significant distance.

Conclusions

A microrobot is being developed based upon the cricket. The robot will fit inside a 5-cm cube and will locomote by walking and jumping. The technologies necessary to construct a pneumatically actuated 5-cm robot are being developed. The motor, batteries and compressor have been shown to be sufficient for the task. In the design of the robot, the cricket's leg kinematics were simplified and yet maintained most of their locomotion functions. A rear leg was constructed and tested. It was shown that two degrees of freedom are sufficient to perform this leg's locomotion functions.

Acknowledgements

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