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A Cockroach Inspired Robot With Artificial Muscles

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Abstract

A robot, CWRU Robot V (Ajax) has been constructed based on the death head cockroach, *Blaberus discoidalis*. In an attempt to further take advantage of the neuromechanics of the animal, actuators with muscle-like properties have been employed that demonstrate a superior force to weight ratio over conventional actuation devices. Although it is not feasible to capture the entire range of motion displayed by the animal (seven degrees of freedom per leg), research has shown that twenty-four degrees of freedom provide a sufficiently close approximation for agile walking and climbing. The fifteen kilogram robot has an offboard power source and control system. Preliminary tests show that it is capable of maintaining stance and lifting significant payloads, as well as rough, open-loop walking.

1. Introduction

The concept of a fully autonomous, mission capable, legged robot has for years been a Holy Grail of roboticists. Development of such machines has been hampered by actuators and power technology and control schemes that cannot hope to compete with even some of the "simplest" systems found in the natural world. Faced with such a daunting task, it is not surprising that more and more researchers are beginning to look toward biological mechanisms for inspiration.

Biology provides a wealth of inspiration for robot design. There are millions of species of animals that have evolved efficient solutions to locomotion and locomotion control. Insects in particular are well known not only for their speed and agility but also for their ability to traverse some of the most difficult terrains imaginable; insects can be found navigating rocky ground, walking upside down, climbing vertical surfaces, or even walking on water. Furthermore, insects almost instantly respond to injury or removal of legs by altering stance and stepping pattern to maintain efficient locomotion with a reduced number of legs [1]. Given the ultimate goal of autonomy, this ability to reconfigure locomotion strategies will be crucial to the robustness of autonomous robots [2].

There are of course other mechanisms capable of producing locomotion, most notably wheels and caterpillar treads. While these devices are admittedly much easier to design and implement, they carry with them a set of disadvantages that inhibits their use in military or exploratory applications. Primary amongst these limitations is the simple fact that wheels, and to a lesser extent treads, are not capable of traversing terrain nearly as complex as that which a legged vehicle is capable of maneuvering over [2]. Even wheeled and tracked vehicles designed specifically for harsh terrains cannot maneuver over an obstacle significantly shorter than the vehicle itself; a legged vehicle on the other hand could be expected to climb an obstacle up to twice its own height, much like a cockroach can. This limitation on mobility alone means that in any environment without fairly flat, continuous terrain, a walking vehicle is far preferable to a wheeled or tracked one. Legged vehicles are also inherently more robust than those dependent on wheels or tracks. The loss of a single leg on a hexapod will result in only minimal loss in maneuverability; on a wheeled vehicle a damaged wheel could spell the end of mobility, and a damaged caterpillar tread almost always results in catastrophic failure. Finally, legged vehicles are far more capable of navigating an intermittent substrate—such as a slatted surface—than wheeled vehicles [3].

Given the preceding argument for the use of legged locomotion in certain environments, one is left with the daunting task of actually designing an efficient legged robot. While such a task is difficult to say the least, nature has provided us—literally—with a world full of templates. Animals can be found that are capable of navigation over almost any surface, and it is from these natural solutions to locomotion problems that engineers are more and more often seeking inspiration.

2. Actuator Selection

The selection of actuators plays a pivotal role in any mobile robot design, as the shape, size, weight and strength of an actuator must all be taken into account, and the power source of the actuators often provides the greatest constraint on a robot's potential abilities. Biological organisms have a great advantage over mechanical systems in that muscle, nature's actuator of choice, has a favorable force-to-weight ratio and requires low levels of activation energy. Their tunable passive stiffness properties are also well suited for energy efficient legged locomotion. The most frequently used actuators, electric motors and pneumatic/hydraulic cylinders, are far from equivalent to their biological counterparts.

Electric motors are probably the most commonly used actuation and control devices in modern day robotics, and with good reason. Motors in a wide range of sizes are readily available and they are very easy to control. These devices are also fairly easy to implement, normally requiring just a few electrical connections. However, electric motors have several disadvantages. Most importantly, their force-to-weight ratio is far lower than that of pneumatic and hydraulic devices, and in a field such as legged robotics, where weight is of the utmost importance, this makes them unsuitable for many applications. Typically, electric systems have a power to weight ratio of 50-100 W/kg (including only motor and gear reducer, operating at rated power), whereas fluid systems produce 100-200 W/kg (including actuator and valve weights) [4] and biological muscle, which varies widely in properties, produces anywhere from 40-250 W/kg [5]. In addition, when trying to take advantage of an animal's efficient biomechanical design, the drastic difference between the rotary motion of most electric motors and the linear motion of muscle can cause complications.

Pneumatic and hydraulic cylinder systems eliminate some of the problems associated with electric motors [6]. As a general rule, they provide a significantly higher force-to-weight ratio than motors; an advantage that in itself often leads to their use, even given the increased complexity and weight of control valves and pressurized fluid lines required for operation. These actuators also produce linear motion, which makes them more suitable to serving a role equivalent to muscle. Unfortunately, air cylinders are better suited to "bang-bang" operation; that is, motion from one extreme to another with mechanical stops to halt motion. Smooth walking motion requires a much larger range of states, and the stiction present in most pressure cylinders makes even course position control difficult. Fluid pressure devices are still quite massive; for example, almost seventy-five percent of CWRU's Robot III's weight is composed of its actuators and valves [7].

Braided pneumatic actuators (BPAs) provide a number of advantages over conventional actuation devices, and share some important characteristics with biological muscle. These devices consist of two major components: an inflatable bladder around which is wrapped an expandable fiber mesh (Figure 1). The resulting actuator is significantly lighter than a standard air cylinder; however, the braided pneumatic actuator is actually capable of producing greater forces (and thus possesses a much higher force-to weight-ratio) than its heavier counterpart. When the bladder is filled with pressurized air, its volume tends to increase. Because of the constant length of the mesh fibers, this can only be accomplished by the actuator expanding radialy while simultaneously contracting along its axis. The result is a muscle-like contraction that produces a force-length curve akin to the rising phase of actual muscle [8]. An important property of BPA to note is that at maximum contraction ($L/L_o \approx 0.69$) the actuator is incapable of producing force; conversely, the maximum possible force is produced when the actuator is fully extended. Therefore, similar to muscle, the force output of these actuators is self-limited by nature. While an electric motor controller could conceivably become unstable and drive a system until failure of either the structure or the motor, a braided pneumatic actuator driven by an unstable controller is less likely to be driven to the point of damaging itself or the surrounding structure. Because of this property, braided pneumatic actuators are well suited for the implementation of positive load feedback, which is known to be used by animals including cockroaches, cats and humans [9]. BPAs are also known as McKibben artificial muscles [10], air muscles, and rubbertuators. They were patented in 1957 by Gaylord and used by McKibben in orthotic devices [11].

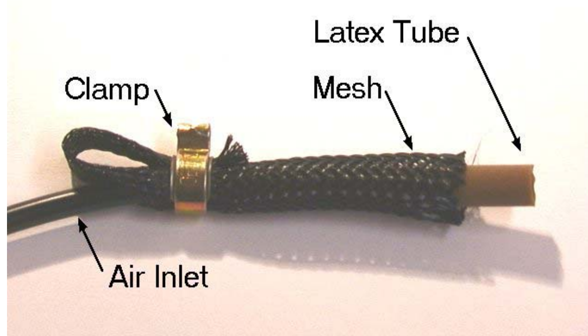

Figure 1: A cut away view of a braided pneumatic actuator

Like biological muscle, BPAs are pull-only devices. This means that they must be used in opposing pairs, or opposing some other antagonist. This property is of significant importance for useful application of these devices, for although it requires the use of two actuators or sets of actuators at each joint, it allows the muscle-like property of co-contraction, also known as stiffness control. If one considers a joint in the human body, such as the elbow or knee, it should be obvious that whatever position the joint is in the muscles that control that joint can be activated (flexed) without changing the joint angle. From an engineering standpoint, this is accomplished by increasing the force produced by each muscle in such a way that the net moment produced at the joint is zero. As a result, the joint angle remains the same but perturbations, such as the application of an outside force, result in less disturbance. From a practical standpoint, this means that the joint can be varied through a continuum of positions and compliances independently. The resulting joint can be stiff when needed, such as when bearing weight while walking, or compliant, as in cases of heel strike where compensation for uneven terrain may be needed.

The greatest impediment to widespread use of BPAs has been their relatively short fatigue life. Under operating conditions such as we desire, these devices are capable of a service life on the order of 10,000 cycles as they were originally designed. A significant improvement to these devices has been made by the Festo Corporation, which has recently introduced a new product called fluidic muscle. This operates on the same principles as a standard BPA, with the critical difference being that the fiber mesh is impregnated inside the expandable bladder. The resulting actuators have a demonstrated fatigue life on the order of 10,000,000 cycles at high pressure.

3. Previous Robots

Two previous robots developed at CWRU have provided significant insight and impetus for the design of Robot V. Both of these cockroach-based robots are non-autonomous, and rely on off board controllers and power supplies for operation.

Robot III was the first pneumatically powered robot built at CWRU, and relied on conventional pneumatic cylinders for actuation. This 15 kilogram robot was powerful, and was demonstrated to be capable of easily lifting payloads equivalent to its own weight. The fundamental failing of this robot was the difficulty inherent in the control of the pneumatic cylinders; although capable of maintaining stance robustly and cycling its legs in a cockroach manner, to date this robot has not demonstrated smooth locomotion [12].

Kinematically similar to its predecessor, Robot IV implemented braided pneumatic actuators in place of Robot III's pneumatic cylinders. This robot was underpowered; it was barely able to lift itself, the valves were moved off-board for walking experiments. However, this robot was significantly easier to control, in large part because the valves allowed air to be trapped inside the actuators, so that joint stiffness could be varied as well as joint position. Using an open-loop controller, this robot was able to locomote [13]

4. Overview of Robot V Design

Case Western Reserve University's most recent robot, Robot V (Ajax) like its predecessors Robot IV and Robot III is based on the death head cockroach *Blaberus discoidalis*. Although it is not feasible to capture the full range of motion exhibited by the insect—up to seven degrees of freedom per leg—analysis of leg motion during locomotion suggests that this is not necessary. This is because in many cases joints demonstrate only a small range of motion, while the majority of a leg's movement is produced by a few joints. We have determined that three joints in the rear legs, four in the middle legs, and five in the front legs are sufficient to produce reasonable and robust walking [7] [14].

The different number of DOF in each set of limbs represents the task-oriented nature of each pair of legs. On the insect, the front legs are relatively small and weak, but highly dexterous (Figure 2), and are thus able to effectively manipulate objects or navigate difficult terrain. This dexterity is attained in the robot through three joints between the body and coxa. These joints are referred to (from most proximal to most distal) as γ, with an axis parallel to the intersection of the median and coronal planes (in the z direction); β, with an axis parallel to the median and transverse planes (in the y direction); and α, with

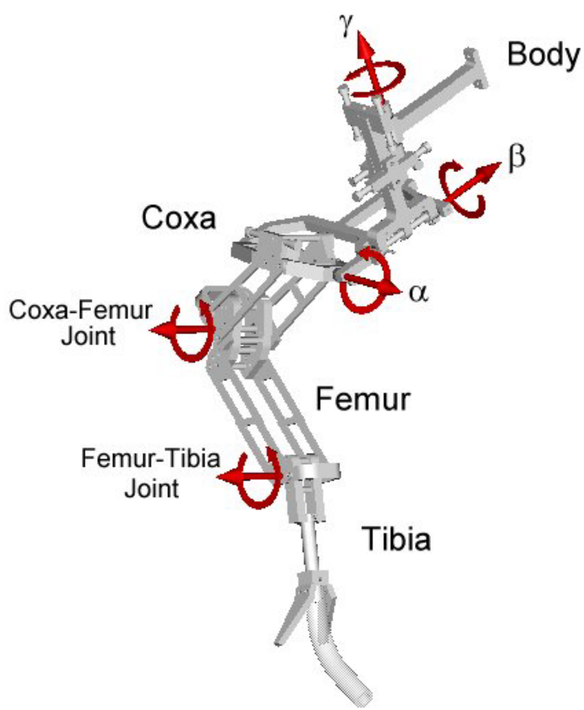

Figure 2: Schematic of front leg with axes of joint rotation

an axis parallel to the coronal and transverse planes (in the x direction). The two remaining joints are between the coxa and femur and the femur and tibia. The middle legs on the insect play an important role in weight support, and are critical for turning and climbing (rearing) functions; however they sacrifice some dexterity for power. On Robot V, the middle legs have only two degrees of freedom—α and β—between the body and coxa, and retain the single joint between the coxa and femur and the femur and tibia. Finally, the cockroach uses its rear legs primarily for locomotion, and although these limbs are not as agile as the others, they are larger and much more powerful; likewise, the rear legs of the robot have only one joint between each of the segments. The body-coxa joint uses of only the β joint.

Although each leg has a unique design, one component they have in common is the tarsus, or foot, construction. This consists of a compliant member attached to the end of the tibia and a pair of claws. The compliant element is capable of bending to maintain contact with the ground, thus providing traction. The claws are angled differently on each leg to assist in its specific task; for example, the claws on the rear leg are angled backwards like spines, allowing the foot additional traction when propelling the robot forward.

4.1 Valves

Each joint is driven by two opposing sets of actuators, allowing for controlled motion in both directions (previous robots have used a single actuator set paired with a spring) [15]. Each actuator set is driven by two two-way valves; one for air inlet and one for air exhaust. This scheme doubles the number, and thus the weight, of valves as compared to Robot III; however, it allows for the implementation of stiffness control, or co-contraction. Because the pressures in opposing actuators can be independently varied, the same joint angle can be achieved using different combinations of actuator pressures; all that is required is that the moments on a given joint sum to zero at the desired position. As a result, a joint can be made very stiff by pressurizing both sets of actuators, or very compliant, by pressurizing one actuator only enough to overcome the mass properties of the limb to reach a desired position.

4.2 Stance bias

The actuators onboard a legged robot can generally be subdivided into two classes: those used to move the limb through the swing phase and those required to maintain stance and generate locomotion. One of the fundamental differences between these two types of actuators is the load that is required of them. The swing actuators need only provide the force necessary to overcome the weight and inertia of the limb, whereas the stance actuators must support not only a significant portion of the entire mass of the robot, but also provide the force necessary for locomotion. This disparity between operational demands can potentially lead to large, powerful stance actuators and small swing actuators (as can be seen in the human body with powerful quadriceps muscles which maintain stance, and the respectively weaker hamstring muscles, which are used for swing); however, because of limited options for robot actuator sizes, it is more often the case that the swing actuators are overpowered, whereas the stance actuators are either underpowered or just capable of meeting the demands placed on them.

On Robot V this problem was resolved through the placement of torsion springs at some critical load bearing joints (specifically the coxa-femur and β joints) to provide a bias in the direction of stance. As a result, the forces required of the stance actuators are significantly reduced while the swing actuators must produce greater forces, but still remain within their operational range.

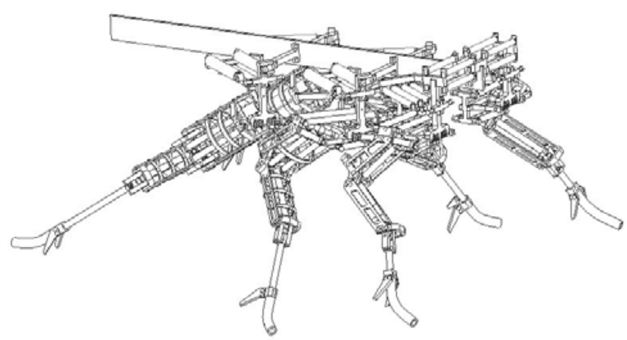

Figure 3: Robot V (Ajax)

5. Initial Trials

Robot V, like Robot IV, was designed as an exoskeleton, where the structural members are placed outside and around the actuators. Not only did this allow a significant reduction in weight, but it also provided a limited protection for the actuators, which are susceptible to puncture and abrasion (Figure 3). The vast majority of the structural elements were made of 6061-T6 Aluminum, although axles and actuator mounting shafts were made of 1018 steel, and fasteners were made from stainless steel. All joint axles were mounted in nylon journal bearings.

Whenever possible, actuators were directly mounted to both their insertion and their origin. This precluded the need for tendons, allowing the maximum possible length of actuator to be used. This in turn maximized the force and stroke available for each individual joint. The notable exception to this strategy was the β actuators, which were attached to a tendon and mounted parallel to the body. This was done to reduce the overall height of the robot.

The first legs to be built were the middle legs. These were chosen for initial tests because they must be dexterous and forceful to maintain stance in a tripod gait. After completion of the first leg the range of motion (ROM) of each of its joints was measured and compared to the design values. These data are summarized below:

Joint	ROM	Desired ROM
β	20°	30°
α	25	40
c-f (coxa-femur)	40	50
f-t (femur-tibia)	75	75

These tests were performed at both 5.5 and 6.25 bar, with no significant difference between the results of the two, suggesting that at these pressures the actuators had reached their full contraction. Although the desired ROMs were not reached, the measured ROMs are in excess of those demonstrated by animal. The demonstrated ROM's of the leg were deemed sufficient for walking and climbing.

A gantry was constructed to support the middle legs for preliminary stance and motion tests. With only horizontal support—to prevent tipping—the legs were able to maintain stance while supporting their weight (three kilos) plus the weight of the valves for the actuators (one half kilo) and a gantry element (one kilo) without any pressurized air in the actuators. This capability, a result of the aforementioned stance bias, clearly demonstrates the ability of these legs to support not only the weight of the robot, but a significant payload as well. An open loop controller was then used to cycle the legs through "push-ups"; raising themselves from a minimum to a maximum height. In this fashion, the legs were able to lift the body approximately 6 cm. This process was repeated with additional payloads (beyond valve and gantry weight) of two and a half and five kilograms using 6 bar air. In both cases, the legs were able to attain the same height.

6. Ajax

Fully assembled—including valves—Robot V weighs 15 kilograms. Range of motion tests have been performed for all joints, and are summarized below. In many cases, specifically the femur-tibia joints of all legs, these ranges of motion are in excess of the desired ROM. In all cases, they are sufficient for walking and climbing.

JOINT	ROM
Front Leg	
γ	35°
β	45
α	25
c-f	40
f-t	75
Middle Leg	
β	20
α	25
c-f	40
f-t	75
Rear Leg	
β	25
c-f	50
f-t	80

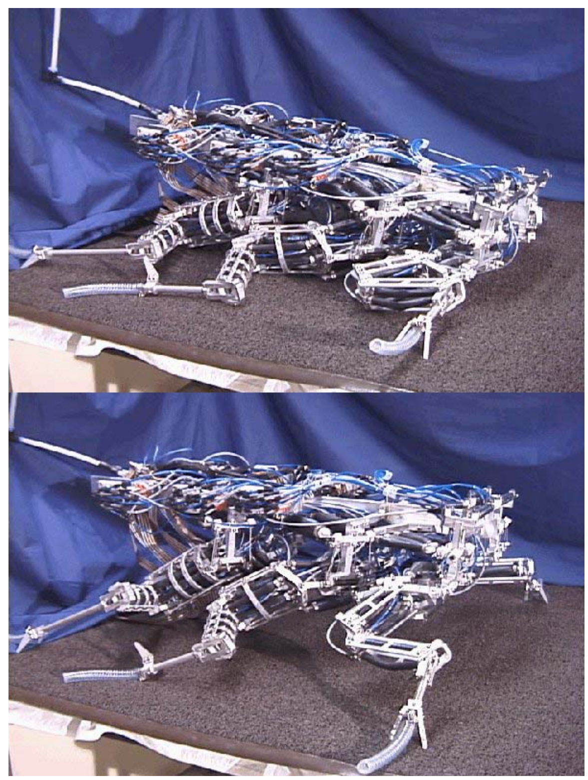

Figure 4: Robot V without activated actuators (top) and standing (bottom). Note that even when the actuators are un-pressurized, they maintain a near-stance position, with only the feet contacting the surface.

Ajax demonstrates a propensity to stand due to the preloads placed on the torsion springs; even without pressure in the actuators, the middle and rear legs maintain a near-stance position. Initial tests of the robot have shown that it is capable of supporting its weight in a standing position and of achieving stance both unloaded and with a five kilogram payload (Figure 4). Further tests have shown that the robot is able to achieve a tripod stance and alternate between tripods, which is important for walking. These tasks were achieved using a simple open loop controller. Furthermore, the passive properties of the BPA's are clearly highlighted in the robot's ability to return to its desired position after suffering perturbations without the use of any form of active posture control.

Using a feed forward controller with absolutely no feedback, the robot can produce reasonable forward locomotion. Although this is by no means the robust, agile walking that is the ultimate goal of this project, it is a clear demonstration of not only the robot's capabilities, but also the advantages offered by the BPA's. The ability to move using only an open loop controller is in large part a result of the passive properties of the actuators, which provide compensation for any instabilities in the controller itself and immediate response to perturbations without the need for controller intervention. This can be contrasted with Robot III, which, even with kinematic and force feedback, was not able to walk. This failure of Robot III is attributed to the inability of both the pneumatic cylinders and posture controller to deal with the sudden changes in load associated with locomotion. In short, the BPA's act as filters, providing immediate response to perturbation; a task the controller is incapable of. This same process occurs in biological muscle, which responds nearly instantaneously to perturbation, but only slowly to neurological input [16]. With the addition of a biologically inspired closed loop controller in the future, Ajax is expected to display robust, insect-like locomotion.

7. Future Work

Although the mechanical aspects of this robot have been completed, the control system is still in its infancy. Because the mechanics of a system are inextricably linked to its control circuits, Ajax's controller is expected to benefit from the close relationship between its design and that of the actual insect. This relationship is perhaps most prominent in the muscle-like nature of the braided pneumatic actuators.

Sensors will be added to provide not only joint position feedback, but force feedback as well. Joint angle can easily be determined with a potentiometer, as has been done on our previous robots. Force feedback will be attained through pressure measurements from the actuators, which, given actuator length, can be used to determine actuator force. Although strain gauges properly placed on the mounting elements of the actuators can produce sufficient force feedback, previous work has shown many desirable characteristics inherent in pressure transducers: they have much cleaner signals, do not require amplifiers, and do not exhibit cross talk; all disadvantages of strain gauges. In addition, strain gauges must be mounted directly adjacent to the actuator they are recording from; this requires more weight at distal points of the limb, (thusly increasing the moment of inertia of the limb) and generally reduces the usable available stroke of the actuator. We have demonstrated that a pressure transducer located down-line from an actuator produces a sufficient signal to determine actuator force.

An insect-inspired controller was developed for Robot III, and this will be modified for use on Robot V. It is a distributed hierarchical control system. The local to central progression includes circuits that control joint position and stiffness, inter-leg coordination and reflexes, intra-leg gait coordination, and body motion. The inter-leg coordination circuit solves the inverse kinematics problem for the legs and the centralized posture control system solves the force distribution problem.

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