Biomimetic robots for robust operation in unstructured environments

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Abstract

Animal models are used as the inspiration for many different types of robots by closely studying the mechanics of various animals and then applying these observations to robot design. The goal is to develop a new class of biologically-inspired robots with greater performance in unstructured environments, able to respond to changing environmental factors such as irregular terrain. Unlike traditional science fiction views of robots that closely resemble animals in outward appearance, this has used biomimicry of the cockroach, one of nature's most successful species. Insects are studied to understand the role of passive impedance (structure and control), humans are studied to understand adaptation and learning. Novel layered prototyping methods are used to create compliant biomimetic structures with embedded sensors and actuators. Biomimetic actuation and control schemes are developed that exploit "preflexes" and reflexes for robust locomotion and manipulation. Preliminary experiments are carried out to determine insect leg properties. The first prototypes of embedded sensors and actuators are illustrated. Locomotion focus: rough terrain traversal, inspired by the cockroach running over blocks surface.
Keywords: hexapedal, tripod, legged locomotion, mobile robot motion and path planning, modelling.

1 Introduction

Design guidelines for small and fast robots capable of fault-tolerant action in known and unstructured environments are very demanding. Many of these robots

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are legged, leading to the control problem associated with balance and locomotion. With many legs, postural stability can be attained. On the other hand, stable locomotion cannot be solved only by body design. It requires a reconfigurable controller that can handle locomotion with variation in ground slope, payload mass, speed, etc. In this paper, I described tools to build a controller for such a running robot, using only experimental data without precise knowledge of robot dynamics and running behavior of arthropods. Although it is clear how a biomimetic legged robot should react with its environment while running, the design of such systems remains a challenge. Available power sources and actuators are less efficient than what is observed in nature. The size-to-payload ratio of actuators, their drives, and energy storage are high, compared with muscles. One approach is to make a Functional copy of the anima. Designing controllers that deliver some of the versatility inherent in the animal motor-control system, especially regarding motor learning, adaptation, and motion planning, might be a useful first step. The biomimetic principles in the design of a running insect-like robot and its controller have already proven to be a promising design guideline. An insect of choice for building fast biomimetic robots is the cockroach. It has a relatively simple motor-control system and yet it displays extraordinary speed and dexterity, even over rough terrain. In fast runs, it maintains its center of gravity low to support dynamic stability. The oscillations of the pitch yaw and roll rotational movements of the body are modest, thus saving energy. For a robust run, each leg of the tripod in the cockroach firm contact with ground. Instead, it uses kinetic energy to bridge from one firm contact to another. The controller design of a cockroach-like robot might be based on the observation that in walking and running, a cockroach uses a tripod gait with one middle leg on one side acting as virtual legs in an equivalent biped run. Even when negotiating a curve, the stable tripod gait may be a proper walking policy. General parameters that described the tripod gait are stride period, which is the time interval between two activations of one tripod, and duty factor, which is the percentage of time, with respect to half of the stride period that the legs are actively producing force. The robot has six independently actuated legs that rotate with one degree of freedom. The sticks that make up the legs are compliant. The three by three legs rotate in a clock-driven fashion producing alternate tripod gait. The existence of the tripod ensures static mobility. Presently it is capable of achieving five bodies' lengths per second. Its size of nearly half a meter makes it capable of running difficult terrain, even climbing stairs. It control their velocity by the rotation frequency of legs or whegs, and, perhaps, by the physic relationship between the legs.

My effort was a project to build biologically inspired robots that are cheap, fast, smart, compliant and fault-tolerant using mostly off the shelf technology. My approach was to make efficient models of robot-environment interaction for model-based control and locomotion planning under external disturbances such as sloped ground and added payload mass. Controlling of robots made of plastic with poor tolerances is challenging. A way proceed is to mimic a cockroach motor control system. Its locomotion is usually explained by reflexive, spring and damper-like behavior of the leg, responsible for rapid stabilization augmented in certain direction by its motor control system.

2 Design of a hexapedal robot

We used the legs except that the flexures (the compliant area at each joint) were interchangeable, allowing us to examine the role of compliance in stable locomotion. Our robot has a compact aluminum body, different from Sprawl in size, shape, material and weight. It also has six small DC servomotors that act like hips, i.e., they control orientation of each leg in an offline fashion. The DC motors have their own servo controllers that accept serial communication for setting up the posture before the start of the run. Each leg has a one-way air-piston with a reverse spring action, and a passive flexure functioning like a knee. The robot runs by alternate tripod gait. Three out of six legs make one tripod. Two tripods are controlled by two valves. Therefore, we have two control inputs. The valves are powered by a custom design interface logic connected to a parallel PC port. A PC controls the robot by commanding locomotion sequences. The air pressure comes from off board. The tripod activation is defined by Stride Period and Duty Factor (DF) the percentage of time that the valves are kept open during half of the stride period. The motors are used only to fix the orientation of the tethered part of the legs throughout the run. We had two reasons for this: First, from a practical point of view, with the motors we had it would be impossible to position them so quickly within the stride. Second, proper leg orientations are based on measurement of the actual body pitch angle and ground slope. Both of them had to be measured while the robot is still, and it would take a second or two to get reliable readings from the tilt sensors. Hence, by changing the tripod gait between completion of a run and the start of another run, it is possible to download commands from the operator that steers the robot allowing one to achieve a piecewise constant velocity. The result is a robot that runs straight ahead, pauses to change its orientation, and then continues to run. In the next three subsections, we will explain the mechanical design of the robot, and the procedure of modeling posture.

2.1 Mechanical considerations and optimal posture

The backbone of the robot was a thin aluminum bar. Six rectangular aluminum tubes were glued on two sides of the bar. Each held a DC motor that tethered a leg. The leg design is given in Fig. 1. Two air valves were placed on the back of the robot. The 3-way solenoid valves were normally closed. Along with the flexures, they produced a force-moment couple that was transmitted to the body, producing gait. The compliance of the flexure was chosen according to the mechanical roperties of the body and ground. The idea was to choose a compliance that would allow the leg to bend back and return the energy while the piston was still in contact with the ground. Otherwise the energy would be returned too soon or too late, interfering with stride rhythm.

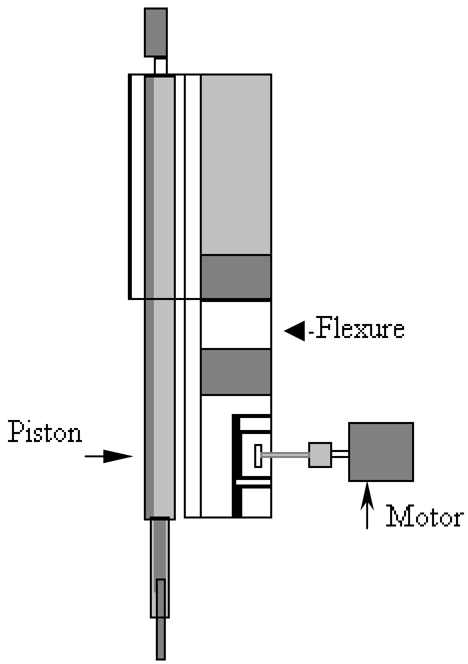

Figure 1: Two views of leg with piston and interchangeable flexure. Lower part of the leg is tethered to the DC motor located beneath body. Legs are modular with a flexure connecting the part with a gear and the part with the piston. Flexures are made in four thicknesses, denoted Types I, II, III, and IV, ranging from 2-3 mm.

Results from bipedal walking as well as studies on hexapod insects suggest that the moment around the center of mass of the body should be as low as possible in order to achieve transfer of impact energy into kinetic energy. Studies on animal walking and running suggest that during locomotion, the point around which there is zero moment is kept within the footprint most of the time. That point is known as the Zero Moment Point. In a tripod gait, the footprint triangle ensures stable stance but not necessarily stable locomotion. Without an exact model of the geometry and masses, and without appropriate sensors, it is impossible to compute the location of the ZMP. Instead, we hypothesized that smooth locomotion would take place if ground reaction forces (in the static case) intersected at one point to form a resultant force that passed through the Center-of-Mass (COM) of the robot. In order to achieve this, let us briefly consider the mechanics of the robot in the static case.

Each leg in the tripod produces a Ground Reaction Force (GRF) that forms a resultant force-moment couple. It is assumed that the GRFs reside in a plane parallel to the sagittal plane. Although the legs are compliant at the knee, the lateral compliance of the leg is negligible compared to the forward/ backward compliance; this is due to the shape of the flexure element (Fig.1). Forces **F**1 and **F**5 are acting from one side of the body while force **F**4 is acting from the other side. We have plotted the projections of the GRF in the lateral plane in Fig. 2A, and in the body plane in Fig. 2B, whereas Fig. 4 shows projections of the GRF in the sagittal plane.

The robot posture is pictured in Figs.2 and 3. Consider one tripod, formed by legs 1, 4, and 5 in contact with the ground. The coordinate system is located at the COM (Figs. 2 and 3). Note that the COM is not located in the middle of the robot; rather it is closer to its tail. A non-zero resultant moment gives rise to the yaw angle. Since tripods are symmetric and act alternatively it is reasonable to expect that a non-zero resultant moment will produce a change of yaw angle that would be cancelled by the opposing tripod. However, due to the flexures in the legs, this cancellation is never perfect, making the robot veer from a straight path, as was experimentally observed. Similarly, the net moment around the *Ox* axis is the result of the vertical component of the GRFs. Moments are denoted by **T**15x and **T**4x (Fig. 2.A). The resultant moment changes the roll angle during a run. This produces a wobbling from left to right. In order to keep wobbling as low as possible, it is desirable to push middle legs further away from robot's longitudinal axis because it is the middle leg that produces the thrust against the two legs on the other side. This also helps reduce yaw oscillations.

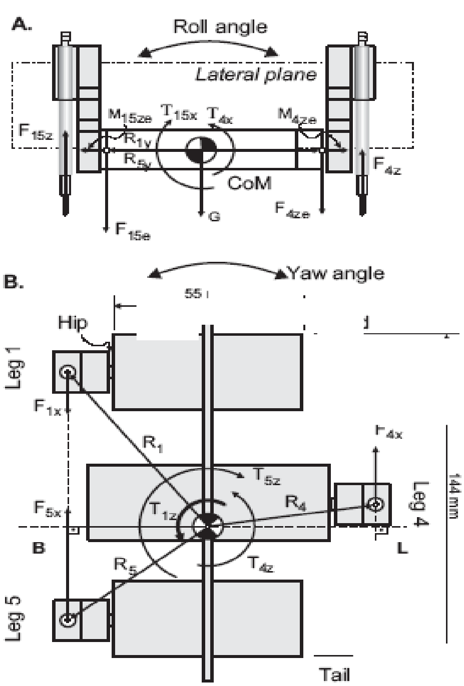

Figure 2: Views of one tripod. Rear view (A) and top view (B) of the robot with only one tripod (legs 1, 4, and 5).

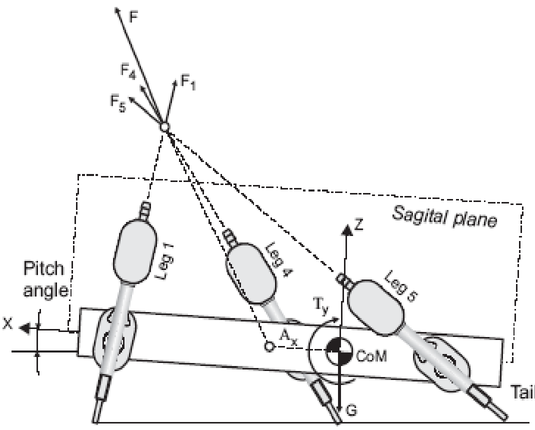

Figure 3: Side view of the robot standing on one tripod. The angle of the resultant force determines locomotion velocity.

2.1.1 Modeling the pitch angle of the robot

The relationship between leg orientation and body pitch angle under gravity load is a non-linear map, mostly due to flexures in the legs. In general, six legs will produce six controllable degrees of freedom of the robot's body. This problem is augmented by engaging synergies. First, we have three by three legs forming tripods and, second, they have symmetrical orientation. We simplified the search for a pitch angle model by keeping the front legs in the fixed position (10° from vertical, tilting backwards). While varying the middle and rear legs, due to compliant legs, we ensured that two constraints were satisfied: (a) all six legs were on the ground and (b) the legs were orientated in such a way that the resultant torque around *Oy* axis at COM was near zero. The flexures used in determining the pitch angle model were chosen among available types III-I-II, III-II-I, and III-II-II, for front-middle-rear legs, respectively. The experimental procedure was as follows: First, middle legs were positioned randomly, and then rear legs were positioned in accordance to constraints. Next, body pitch angle was measured by a tilt sensor. Front legs, left and right, were at fixed position and were not included in modeling. Resulting model can be used in two ways. First, for a desired pitch we can determine legs orientations. Body pitch angles between 3.5° and 7.0° were used in modeling. Data for cross validation included pitch angles ranging from 3° to 7.75°.

2.1.1.1 Key areas in robotics Path planning – given a start location, a goal location and a map, find a (perhaps optimal) path from start to goal. Replanting is often necessary if information about the environment change. Perfect path planning is based on mapping just like 1) Topological mapping – which include distinctive places, connection graph, lessened for accurate location; 2) Geometric mapping in which spatial relationships maintained, uncertainties multiply.

Stereo vision- two cameras at a fixed distance (base line) form each other. Different perspectives of two cameras (right and left) lead to relative difference between the location of the same object in two images, which varies by distance.

Colors vision- composed of red, green and blue (rgb) components. By knowing the color characteristics of an object (and normalizing for light) specific object can be recognized. Solid colors are easy, as shown in fig. 4.

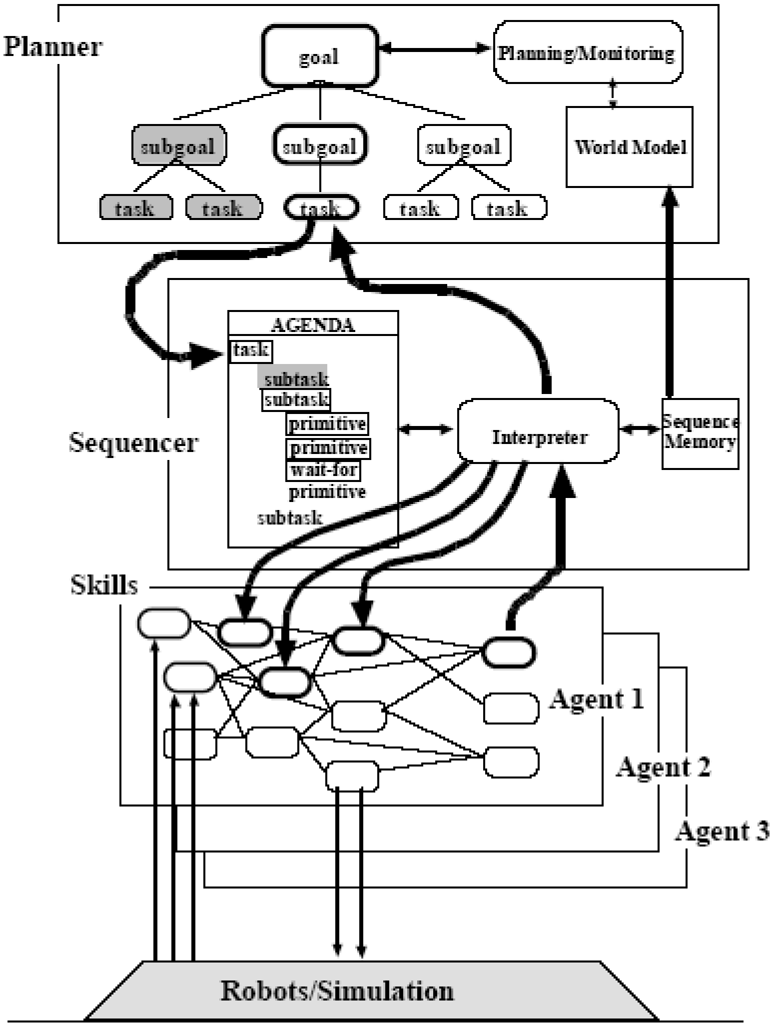

Figure 4: Architectures of path planning, sequencing, control.

3 Conclusion

I presented an approach to the design of a small 6-legged robot. This air-powered robot had six pistons, one per leg, three per tripod with two valves, and one per tripod. Each leg had interchangeable passive flexures connecting tethered parts of the leg with the part that embodied the piston. Small DC motors beneath the body orient the legs in an off-line fashion. The robot moved by hopping from one tripod to another. Our design of robot's body differs from its Sprawl predecessors in two major aspects. All six legs had the same type of flexure. In addition, leg orientations did not follow a specific procedure that might lead to successful running. In my robot, middle legs were pushed backwards, closer to the rear legs, shifting the COM backwards. Several combinations of flexures were tested, leading to conclusion that front legs require higher stiffness, whereas middle and rear legs require softer flexures. I chose leg orientations based on the static analysis, supported by experiments later on, following the constraint that all ground reaction forces of one tripod should intersect in a single point. In this way, ground reaction forces from the tripods did not produce resultant moment at the COM of the robot. I also hypothesized that locomotion velocity may be controlled by changing the angle of the remaining resultant forces. My goal was to apply parametric modeling tools to build a feed-forward locomotion velocity model with typical task parameters: ground slope and payload mass. The only parameter in the model that I used to control the robot's performance was body pitch angle. Body pitch angle is set up by leg orientation at the beginning of the run. My kinematic model used polynomials to approximate experimental data. Once formed, the model allowed us to compute how the legs should be oriented in order to achieve desired body pitch and consequently locomotion velocity. The pitch angle model embodies information on flexures in each leg. My modeling used a modified version of the Successive Approximations algorithm. It also enables refinement of the model as interaction with the environment changes over time and through experience. My experience with this robot suggested that the robot design was robust. Neither the robot nor sensors suffered a failure. Indeed, not a single screw fell off. The legs and body remained in excellent condition. This robustness suggested that the technology applied in the design can produce robots that are genuinely durable. Altered environment conditions, minor changes in robot design parameters may also benefit of the proposed parametric modeling procedure.

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