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Modeling of Insect's Legs by Inverse Kinematics Analysis

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Abstract

This paper presents a motion analysis of a cricket's legs during walking. An experiment was set up to study the locomotion of crickets walking on a treadmill. Their motions were recorded using high-speed video. The body, foot, and joint motions were digitized. The resulting data were analyzed using an inverse kinematics method to solve for joint angles. The models of the legs were simplified and assumed to have two segments and three joint degrees of freedom.

1. Introduction

In recent years, engineers have become more interested in insects locomotion because the insects are extremely agile and good maneuvering over rough terrains [7, 8, 9]. There are several reasons that legs are better suited to the task of locomotion than wheels or tracks. For example, a legged vehicle can step over obstacles, climb up and down stairs, and go over extremely broken ground.

There is no doubt that wheels are a much faster means of transport over smooth terrain than legs, but wheeled mobility is limited across broken terrain. Moreover, wheels require adequate traction in order to propel a vehicle forward. They also tend to disturb the terrain more than legs [12].

In walking, the legs on the ground support and drive the body forward while the others in the air are swung forward for the next step. This repetitive pattern of foot placements is called gait. There are many kind of gaits for example, the tripod gait [2], where the front and rear legs on one side, along with the middle leg on the other side, support and propel the animal while the remaining three legs (the other tripod) swing forward [5].

Legged locomotion seems to be simple at first glance because nature accomplishes this feat with ease. However, studies of walking and running in animals show that it is more complex than it first appears [3]. There are two different kinds of legged locomotion; statically stable and dynamically stable. In statically stable locomotion the animal maintains its balance by using a wide base of support and locates the center of mass inside the polygon of support provided by touch-down points of the feet. There must be at least three feet in contact with the ground to form a polygon. In dynamically stable locomotion the inertial forces caused by acceleration are significant and the center of mass can move outside of the polygon of support. The leg arrangement is also an important factor in stability. Mammals' legs are more vertical than those of insects, which reduces the bending stress on the leg bones and muscle power required to hold up the body. In contrast, insects have a sprawled posture, which produces considerable lateral forces. These forces increase passive stability and active maneuverability of locomotion. [4].

Developing a robot based upon an insect is a challenging task because insects are complex animals. They have seven joint degrees of freedom in each of their legs. Because of this complexity we use intelligent biological inspiration to extract the principles of insect locomotion and implement them into robots. In this paper we show that a simplified joint configuration can enable cricket foot motions.

2. Biological Studies

2.1. Insect morphology

Structurally, insects are usually long and bilaterally symmetric; the left and the right sides of the body are identical. Insects have six legs, which they use to stand in sprawled postures. The sprawled legs are able to absorb the sideways motion and help keep the center of mass over the polygon of support [11].

We chose to study the cricket as inspiration for small robot design because crickets can both walk and jump well. An insect body consists of three main segments: the head, thorax, and abdomen, as shown in Figure 1.

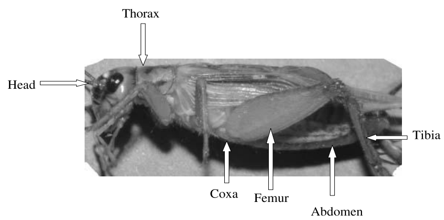

Figure 1: General structure of a cricket

Their three pairs of legs are attached to the thorax. Each leg consists of multiple segments which enable different functions. For instance, the front leg can be used in walking and other activities such as exploring, orientation and eye or antenna cleaning. The front leg joints has far more movement than the middle and rear legs [6].

In the hind leg of the cricket, a large muscle is important for jumping and kicking behaviors. Each leg has four main segments: the coxa, trochanter, femur, and tibia and a set of small segments forming the tarsus [10] as shown in Figure 2. The coxa is attached to the thorax by a three degree of freedom (DOF) joint.

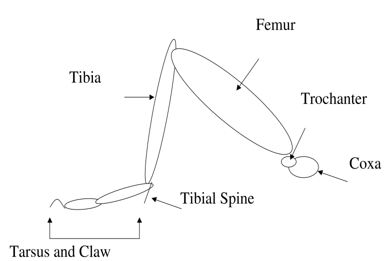

Figure 2: **Cricket Leg Schematic**

The cricket's coxa is short compared to that of the cockroach. The small trochanter segment is attached to the coxa by a single DOF joint. The femur is attached to the trochanter by another single DOF joint, which permits small motions. The cricket's femur is its longest segment. The tibia is connected to the end of the femur with one DOF and the tarsus (foot) is at the distal end of the leg. The tarsus has a spring-like structure.

2.2. Methodology

An experiment was set up to study the locomotion of the cricket walking on a treadmill. The observation and measurement of the legs and body movement was done by using high speed video. This work was performed in the Ritzmann lab in the Biology department at Case Western Reserve University.

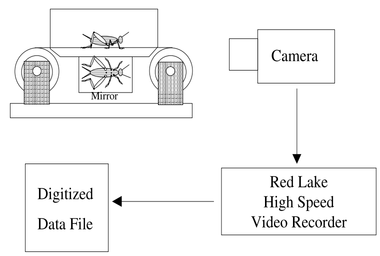

Figure 3: **Experimental setup**

The cricket walked on a treadmill with a transparent belt. A single camera faced the side of the cricket. It is important to observe the movement in two orthogonal planes simultaneously in order to achieve a three-dimensional view. Therefore, a mirror was installed at a 45 degree angle underneath the transparent belt to observe the bottom view. The camera captured the side view and the reflected bottom view, simultaneously. The experiment was set up as shown in Figure 3

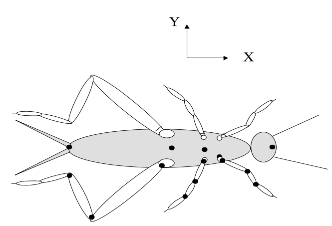

Figure 4: **Cricket schematic bottom view where black dots represent digitization points**

Because the insect's leg movements are so rapid, a high-speed video Redlake Motionscope high-speed video system was used at 250 frames per second. The purpose was to record the movements of points on the cricket's body and legs as it walked.

The cricket was marked at each joint with a small dot of white paint at the locations represented by black dots in Figures 4 and 5. Two points were marked on the body at the head and the end of the abdomen and four points were marked on each leg at the body-coxa, coxa-femur, femur-tibia, and tibia-tarsus joints. Digital video was recorded as the cricket moved on the treadmill surface.

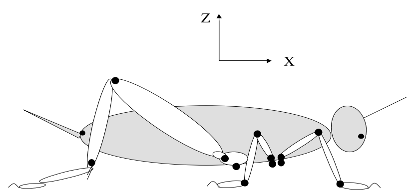

Figure 5: **Cricket schematic side view**

3. Leg Model

In this case we use methods that reduce the complexity of the animal, yet preserve the basic function. We used a leg model with 2 segments and 3 degrees of freedom (DOF) and fit its foot motion to the foot motion of the animal. The kinematics of the leg model will be different from those of the animals, but the foot motions will be the same.

The coxa and trochanter segments are very small and for simplicity we have neglected them. The legs of the cricket were modeled with two segments (femur and tibia) and three DOF, two at the body-femur joint and one at the femur-tibia joint. Using inverse kinematics, the three joint angles of this simplified cricket leg can be determined by given the end point motion of the tibia from the digitized data. The joint angles are α_1, γ_1, at the body-femur joint and α_2 at the femur-tibia joint which rotate about the X, Z and X axes respectively. A simple model of a two bar linkage with these DOF is shown in Figure 6 where link 1 represents the femur segment and link 2 represents the tibia segment.

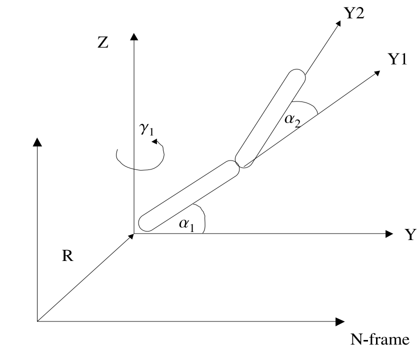

Figure 6: **Two bar linkage represents the femur and tibia segments**

The position vector $\vec{r}$ of the foot at the end of link 2 can be written as the following

$$\vec{r} = \vec{R} + C_{N1}\vec{L}_1 + C_{N2}\vec{L}_2 \qquad (1)$$

where $\vec{R}$ is the position vector from the origin of the N frame to the origin of the 1 frame

$C_{N1} = Rot_z(\gamma_1)Rot_x(\alpha_1)$

$C_{N2} = Rot_x(\gamma_2)$

$\vec{L}_1 = \begin{bmatrix} 0 \\ L_1 \\ 0 \end{bmatrix}$ the length vector of link 1 represented in the 1 frame

$\vec{L}_2 = \begin{bmatrix} 0 \\ L_2 \\ 0 \end{bmatrix}$ the length vector of link 2 represented in the 2 frame then $\vec{R}' = \vec{r} - \vec{R} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$ where

$$x = -\cos(\alpha_1)\sin(\gamma_1)L_1 - \cos(\alpha_1+\alpha_2)\sin(\gamma_1)L_2 \qquad (2)$$

$$y = \cos(\alpha_1)\cos(\gamma_1)L_1 + \cos(\alpha_1+\alpha_2)\cos(\gamma_1)L_2 \qquad (3)$$

$$z = \sin(\alpha_1)L_1 + \sin(\alpha_1+\alpha_2)L_2 \qquad (4)$$

dividing equation 2 by equation 3 we can solve for γ_1

$$\gamma_1 = \arctan\left(\frac{-x}{y}\right) \qquad (5)$$

Substracting equation 2 from 3 yields

$$y - x = (\sin(\gamma_1) + \cos(\gamma_1))\ (\cos(\alpha_1)L_1 + \cos(\alpha_1+\alpha_2)L_2) \qquad (6)$$

Let $u = \frac{y-x}{(\sin(\gamma_1)+\cos(\gamma_1))}$ and using equation 6

$$u = \cos(\alpha_1)L_1 + \cos(\alpha_1+\alpha_2)L_2 \qquad (7)$$

Equations 7 and 4 are solved for α_2

$$\cos(\alpha_2) = \frac{(u^2 + z^2 - L_1^2 - L_2^2)}{2L_1L_2} \qquad (8)$$

$$\alpha_2 = \arccos\left[\frac{(u^2 + z^2 - L_1^2 - L_2^2)}{2L_1L_2}\right] \qquad (9)$$

There is a formula [13] to solve for the angle θ if the equation is in the form

$$a\cos(\Psi) + b\sin(\Psi) = c \qquad (10)$$

$$\Psi = \arctan\left(\frac{b}{a}\right) + \arctan\left(\pm\sqrt{\frac{a^2 + b^2 - c^2}{c}}\right) \qquad (11)$$

Equation 7 can be transformed into the form of 10 from which we can then use the equation 11 to solve for α_1.

4. Foot Trajectories

The foot trajectories are constructed by transforming the digitized data into the body fixed reference frame. The result is plotted as if the animal's body was fixed with its legs freely moving. The " foot" is defined as the end of the tibia. Figure 7 shows a top view of the foot trajectories for the right side of the body, plotted with respect to the body fixed reference frame; X is the longitudinal axis (anterior: positive values); Y is the transverse axis; the Z axis is vertical. The origin is located at the center of the body. Figure 8 shows the side view or X-Z plane. These trajectories are for one representative individual cricket that was observed to walk well.

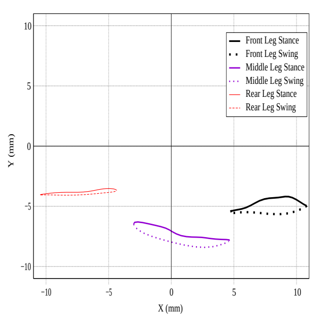

Figure 7: **Foot trajectories for the three feet on the right side of the body, top view or X-Y plane**

As shown in Figure 7, the motions of the hind leg during both the stance (solid line) and swing phases (dotted line) are approximately straight lines. This is not however true for the middle and front legs.

The stance trajectories of the front and middle legs do not follow a straight line as can be seen in Figures 7 and 8. The side view of Figure 8 clearly shows the feet lifting and swinging forward during the swing phase of their trajectories to form elliptically shaped paths. The trajectories in Figures 7 and 8 represent one step, however the four subsequent cycles that were recorded demonstrate similar trajectories.

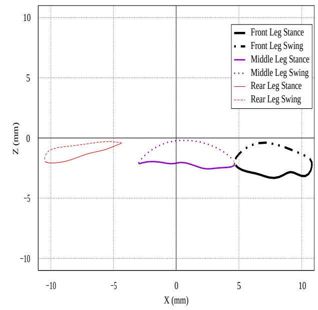

Figure 8: **Footfall trajectory for three feet, side view or X-Z plane**

The origin is located at the center of the body. The stance path shown in the side view of Figure 8 for the back leg has a non zero slope because the digitizing point is at the end of the tibia, which is connected to the tarsus. The tarsus is flexible so the end of the tibia moves vertically as the tarsus flexes.

5. Joint Angle Results

The joint angle motions are obtained by solving the inverse kinematics using the foot trajectories. The foot trajectories have been calculated and are shown in Figures 7 and 8.

Figure 9 shows how the simplified legs angles were defined.

The leg model is reduced to two segments, femur and tibia, and a total of three degrees of freedom; two rotational DOF at the body-femur joint and one at the femur-tibia joint. The results for all three legs are shown in Figures 10, 11, and 12.

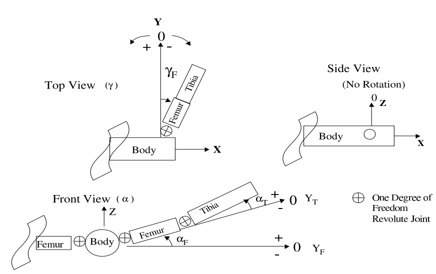

Figure 9: **Leg angles measurement**

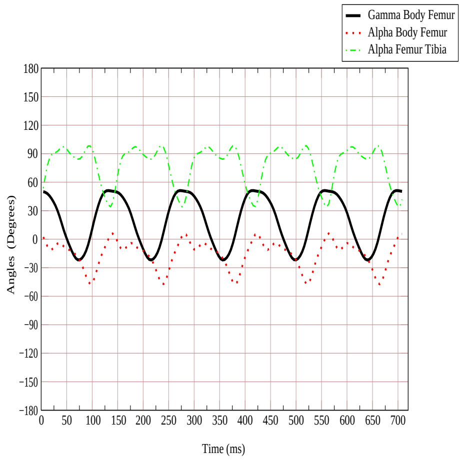

Figure 10: **Front leg with three degrees of freedom**

Figures 10 and 11 show that the joint excursions of all three joints on both the front and middle legs are significant. However the γ in the body-femur joint in the rear leg in Figure 12 is relatively constant at about 75 degrees. This illustrates that the rear leg can be reduced to two degrees of freedom with a fixed γ angle in the body-femur joint.

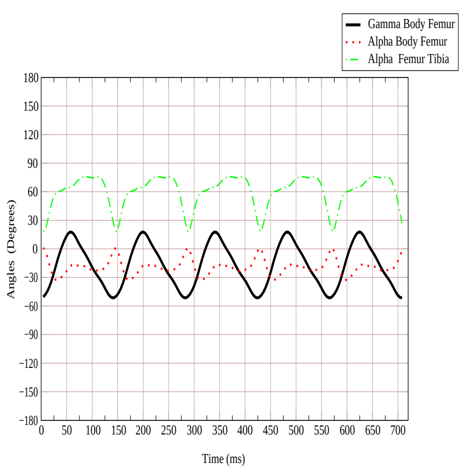

Figure 11: **Middle leg with three degrees of freedom**

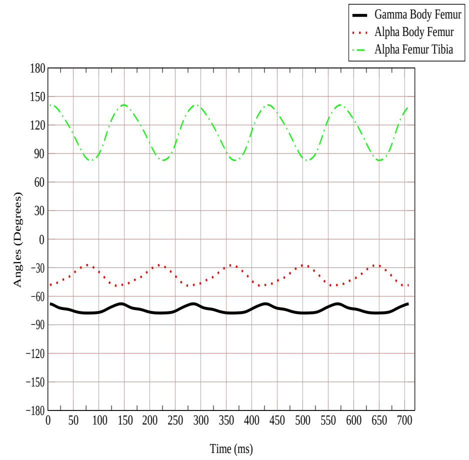

Figure 12: **Rear leg with three degrees of freedom**

6. Discussion

A simplified model of the cricket's legs was developed for the purpose of designing a small robot. Insects have seven joint degrees of freedom in their legs, but all they do not necessarily use all of these joints during normal locomotion. Based upon cricket physiology we modeled its legs with two segments and a total of three joints. An inverse kinematics method was used to determine joint angles that fit the foot trajectory data. The results show that the front and middle legs make use of all three joints to follow the animal's foot trajectories. The rear leg only needs two joints. These results indicate that a cricket inspired robot can be constructed with three degrees of freedom in its front and middle legs and two degrees of freedom in its rear legs. This would give it a total of 16 degrees of freedom. A robot so constructed could move its feet in a cricket like manner and walk in a tripod gait. Our previous results indicated that two degree of freedom rear legs are also sufficient for jumping. The simplifications are important for an autonomous robot because of the associated weight reduction benefits. An 8cm long robot has been constructed based upon these results [1].

Acknowledgements

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