A SIMPLE BIOLOGICALLY INSPIRED WALKING ROBOT

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ABSTRACT

A small walking hexapod robot that is capable of producing relatively high walking speeds is presented. Preliminary estimations show that a walking speed of about 20cm/s is feasible. The leg structure of the robot has been based on that of a fast walking cockroach in order to approximate the accelerating and decelerating forces experienced by a similar biological mechanism. A unique and simple mechanical design is described that produces a type of semi-circular trajectory that the feet will follow. This system will allow the robot to produce the necessary oscillating motion of the feet that can be coordinated for legged locomotion. The same mechanism may be adapted to larger terrain vehicles for rapid walking on open plains.

INTRODUCTION

In recent years the small walking robots that have emerged were impressive but their walking speed was relatively low. Some of these robots include Melwalk Mark-III (Kaneko 1985), Genghis (Angle 1989; Rode 1994), Attila (Angle 1991), Thing (MacDonald 1994) and Boadicea (Binnard 1995). Out of these Boadicea has the highest walking speed of about 10cm/s.

The work presented here describes a simple design for a small robot that is capable of producing walking speeds that exceeds many previous designs. A desired walking speed of about 20cm/s to 30cm/s has been found to be possible for a robot of about 30cm to 60cm in length.

A small hexapod walking robot, named "Strider", was designed and built based on inspirations from the leg structure of a cockroach such as the *Blaberus discoidalis* or the *Periplaneta americana.* A simple drive mechanism (known as the *groove-slot mechanism*) was also designed to propel each of the robot's six legs. It is these two features of the robot that contribute to a faster walking machine. The robot is shown in Figure 1.

The actual legs each use a pantograph mechanism in the longitudinal axis of the robot. The pantograph is used to magnify the semi-circular motion that is produced by the groove-slot mechanism.

The main advantage of the groove-slot mechanism is that no power is required for standing and the amount of payload the robot can carry depends on the structural strength of the groove-slot mechanism. Most previous robots however, require power to be applied to the leg's actuators at all times for the robot to stand (eg. Angle 1989).

One of the main purposes of this work has been to develop a faster walking robot that may lead to newer designs for possible use on both a small and large scale.

This paper will describe in detail the structure and operation of the groove-slot mechanism and explain the advantages of incorporating some of the features of the cockroach in order to obtain more acceptable walking speeds. A brief description of various other functions and aspects of the robot will also be given.

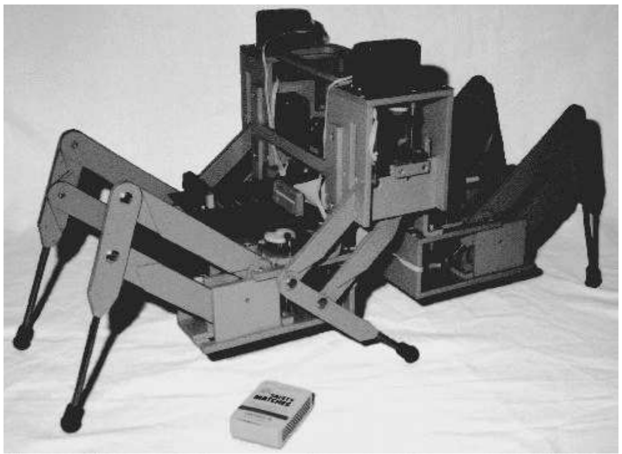

Figure 1: Strider.

A BRIEF DESCRIPTION OF STRIDER

It is difficult to reconstruct an identical mechanical equivalent of the cockroach since we are usually restricted to electric, pneumatic or hydraulic actuation systems. Therefore, the robot would not look or walk like a cockroach to any great extent. Other research has been concerned with imitating the biological mechanical structure of insects however, including the *Carausius Morosus* or the Walking Stick Insect more closely such as (Weidemann 1993).

The robot shown in Figure 1 is made mostly of PVC sheeting. Every PVC component was cut out on a computerised milling machine. The pieces were then screwed together.

The robot has twelve actuators, two per leg. The actuators used are modified model aeroplane servo motors. The gearing inside the servo produces low RPM with a reasonably high torque. Since they were only designed to turn about 120° they were modified to turn 360° for the purposes of this work. Hence, the potentiometer position sensor inside the servos had to be replaced by an external sensor.

The sensors used for the servos were continuous-turn and slider potentiometers that provide two respective voltages for each leg that can be converted to digital numbers relative to the position of the legs.

The robot has an on-board computer that incorporates a 16MHz MC68332 microprocessor, EPROM, RAM, two 8-channel analogue-to-digital converters for the sensors, and six dual h-bridge drivers for the motors. The board has a connection for serial communications and external power. A host computer can communicate with the 68332 for development and downloading of programs.

Since the robot was designed for research purposes only, it was not necessary to have an on-board power supply. Therefore, an external 12V DC power supply was used which in effect reduced the weight of the robot.

Strider's body is 29.5cm long, 14.5cm wide and 19.5cm high. With the legs fully extended in the longitudinal direction, the overall length is about 63cm. Also, with the legs fully extended vertically, the overall height is about 28.5cm. The robot's weight is about 2.28kg.

BIOLOGICAL INSPIRATIONS

Leg Angles

The legs of a cockroach are generally positioned such that the front legs are angled towards the front of the body at all times while walking. The rear legs are angled towards the rear and the middle legs change from pointing forwards to pointing rearwards during a complete stride or step. In effect, while in motion, the front legs decelerate the insect's body, the rear legs accelerate the body and the middle legs both decelerate and accelerate the body (Full et al. 1991). The legs of the robot were angled in a similar way to the legs of the cockroach in order to approximate the acting forces. As can be seen in Figure 2 the front and rear legs always point towards the front and rear respectively during a complete stride. The angle of the middle legs change from pointing forward to pointing rearward in a complete stride, although they are angled less. This, however shouldn't affect the performance of the robot. The reason for incorporating the similar longitudinal leg angles to that of the cockroach, is that legs that push against one another, that produce accelerating and decelerating forces can reduce the overall force production (Full et al. 1991). These observations were made primarily from the *Blaberus discoidalis*. Also, a set of three legs angled in this way together perform the same function as one leg of a biped. Hence, normal walking would be more coherent.

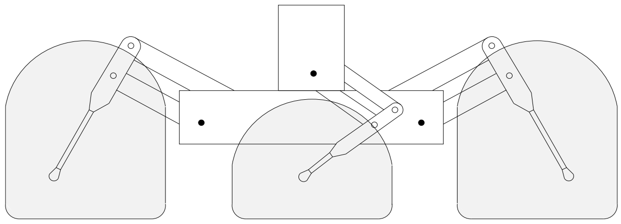

Figure 2: The legs workspaces shown from a lateral projection of the robot.

Although the legs of the cockroach operate in three dimensions, the legs for this robot were restricted to two degrees-of-freedom. The legs can move vertically and in the longitudinal direction, parallel to the body. Movement in the lateral direction (away from the sides of the body) was restricted in order to simplify the operation of the robot. Hence, only the forces acting from a lateral view of a cockroach (Full et al. 1991) have been adapted to this robot.

Leg Sizes

Another inspiration that can be obtained from the cockroach are it's leg sizes. The size of the legs of the cockroach are different as can be seen in the example in Figure 6.

There are several reasons for the cockroach to have long rear legs. Firstly, large strong rear legs are needed to produce fast accelerations. Since the insect's abdomen protrudes towards the rear of the insect, the long rear legs help to keep it from dragging on the ground. Also, since the workspace of the rear leg overlaps the workspace of the middle leg (Binnard 1995), the rear legs, being long, can be used in place of an amputated middle leg to maintain stability while walking.

In contrast, the front and rear legs on Strider are each the same length while the middle legs were made slightly smaller, but only to reduce the height of the robot. High accelerations were not necessary for this robot, and also the body was designed so that there were no protruding masses from the body. Making the workspace of the rear leg overlap that of the middle leg can be a desirable feature. This was not implemented on this robot however, since this research will not be considering the disfunctions of any particular leg. Therefore, for these reasons, there was no need to make the three pairs of legs different sizes for this robot.

THE GROOVE-SLOT MECHANISM

Two or three previous robots such as Melwalk Mark-III (Kaneko et al. 1985) and Dante (Wettergreen et al. 1993) each used a mechanism known as the 4-bar-linkage system that produced a relatively flat semicircular trajectory for the robot's legs. The drive mechanism used for this research is a unique and simple design that produces a similar semicircular trajectory for each leg. This system, known as the groove-slot mechanism, can produce relatively high walking speeds using low RPM, highly geared motors. This mechanism is also responsible for allowing the robot to stand on a horizontal surface without expending power.

Mechanical Description

A pictorial breakdown of the groove-slot mechanism is shown in Figure 3.

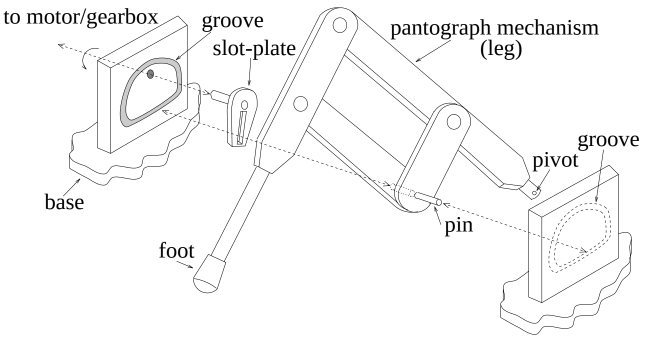

Figure 3: The groove-slot mechanism with one leg.

The groove-slot mechanism is comprised primarily of two parts. A pair of plates with semicircular groove sections, where the groove is cut approximately 3/4 into them, form one part. The semicircular shape has been used since it will allow the robot's foot to move rearward in a straight line on the ground and also allow the foot to be lifted and returned towards the front of the robot for the next step. The other part is simply a plate situated between the two groove plates that has a slot cut into it. The slot plate is pivoted inside the semicircular groove of one of the groove plates. The length of the slot is slightly longer than the maximum radius from the pivot point to the outer edge of the semi-circular groove. A small rod or pin that is as thick as the groove is fitted through the slot plate and into the two groove plates. The semi-circular path can be then traced by the pin by rotating the slot plate about the pivot point, that is, the slot plate will push the pin along the path of the groove and the pin will therefore trace the desired trajectory. Now, by installing the pin into the pantograph leg shown in Figure 4 at point A, the foot of the leg will follow the groove's trajectory and will be magnified by four times.

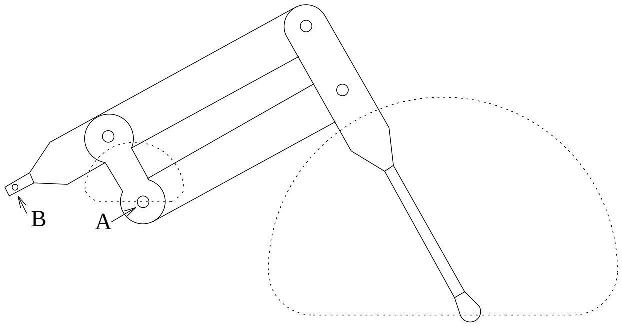

Figure 4: The pantograph mechanism is pivoted at point B. The trajectory at point A is magnified 4 times at the foot.

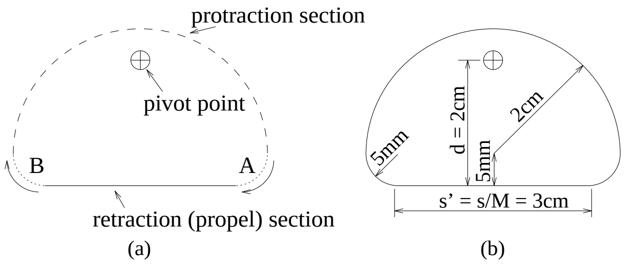

Figure 5: (a) The sections of the groove. (b) The geometry of the groove.

The Reasons for the Shape of the Groove

With reference to Figure 5(a), the groove has a flat, horizontal section which retracts the leg to propel the robot, and a curved section which protracts the leg (moves it from the rear to the front). There are two main reasons for choosing the shape of the groove that produces this foot trajectory.

It was necessary to use a half-circle in the trajectory because of the positioning of the pivot hole. If the hole was made too close to the horizontal (propel) section then the pin would become jammed at either end of the horizontal section. By moving the hole as far away from the horizontal (retraction) section as possible the pin would be less likely to jam. The hole however, had to be within the groove shape so that the rotation of the slot-plate would move the pin along the trajectory. Through experimentation, a distance of 2cm from the pivot point to the centre of the horizontal section was found to be adequate.

The second reason has to do with the two small curved sections shown in Figure 5(a) as dotted arcs. Many walking robots place their feet down before the retraction starts which results in short pauses while walking. The pauses at these leg positions can be avoided to make the walking more coherent by using these two curved sections as described below.

In order to maintain stability while walking using most gaits (or walking patterns), two consecutive legs must retract in sequence for a short duration, that is, one leg should start to retract before the previous leg ends it's retraction. In other words, the two legs must be on the ground at the same time for a short duration. Wilson's diagram (Wilson 1966) shown in Figure 6 shows that this occurs in real insects.

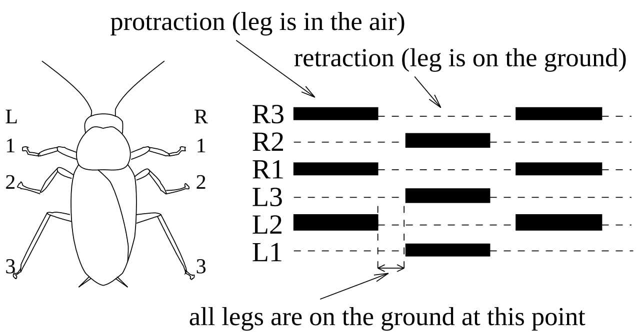

Figure 6: A typical diagram of a cockroach walking with a tripod gait.

Using Figure 5(a) and Figure 6 as an example, by specially coordinating the legs, leg R3 will start to retract before it is placed down as indicated by the arrow in the curved section labelled 'A'. Shortly after this leg is placed down on the ground in its Anterior (front) Extreme Position (AEP), leg R2 will start to lift up from its Posterior (rear) Extreme Position (PEP) as indicated by the arrow in the section labelled 'B'.

Hence, due to the shape of the groove, since the feet are retracting while they are gradually coming in contact with the ground, we have legged locomotion with the characteristic fluent behaviour of wheeled vehicles.

Standing Without Expending Energy and Payload Limitations

The groove-slot mechanism allows the robot to stand without expending any energy. This is a very important feature since many other robots require continuous battery or external power to be applied to at least one actuator to stand at all times.

When Strider is horizontal and stationary, the pin sitting in the retraction section of the groove will have an upwards force due to the weight of the robot experienced on the legs. The pin cannot move vertically in this section and therefore the robot can stand indefinitely.

This is also an advantage while walking since energy is only needed to push the pins and hence move the legs and no extra energy will be used to keep the robot up.

As mentioned above, the amount of payload the robot can carry is mostly dependent on the structural strength of the pin, the groove and the strength of the pantograph legs. However, the friction and inertial properties would become a problem for a large payload and walking speed would naturally have to be reduced.

Since the pantograph mechanisms have a 4:1 ratio, the vertical force exerted at joint A in Figure 4 will be four times larger than that on the robot's feet while standing or walking. The main friction therefore occurs between the pin in each leg and the retraction section of the groove in which it travels through. Graphite powder or grease can be be used to reduce this friction. On a larger scale, more elaborate mechanical devices such as a ball bearing system could be used to reduce the friction.

Determining the Walking Speed

Using Figure 5(b) the maximum retraction speed of the legs can be determined using the following formula:

$$v_{r_{max}} \approx \frac{46.37 s v_m}{\arctan(\frac{s}{2Md})}$$

where

$v_{r_{max}}$ - maximum walking speed of robot (cm/s)
v_m - effective motor/gearbox speed (rev/s)
s - stride length of the robot's foot (cm)
d - minimum groove radius during retraction (cm)
M - magnification factor of the pantograph

The scaling factor in the formula was necessary since the angular distance from the pivot point is smaller for the retraction section of the groove than for the rest of the foots trajectory.

The robot's motors are normally rated at 6V DC. This produces a speed of 0.96rev/s which would produce a maximum walking speed of about 14cm/s. At 11V DC however, the average motor/gearbox speed was found to be about 1.9rev/s. Therefore, the maximum walking speed would be about 28cm/s. Due to loading effects and friction, a somewhat lower walking speed can be expected. By minimising the friction as described above, the robot's speed would be closer to the maximum calculated.

Groove-Slot-Pin Kinematics

The kinematic behaviour of the pin in the groove as the motor turns the slot has been investigated to observe the change in velocity of the pin during retraction. The angle (or rotary position) of the slot-plate determines the current position of the pin and hence the radius from the pivot point to the edge of the groove.

This radius had to be calculated in terms of the angle of the slot plate.

The formulae for the length of the radii is given below. Three sections of the groove were calculated.

With reference to Figure 5(a), r_1 is the radius length of the protraction section, r_2 is the radius length of the section labelled 'A' and r_3 is the radius length of the retraction section. The radius length of the section labelled 'B' will be equivalent to 'A'.

$$r_1 = -15\sin(\alpha) + \sqrt{225\sin^2(\alpha) + 175}$$

$$r_2 = 15\cos(\alpha) - 15\sin(\alpha) + \sqrt{-450\sin(\alpha)\cos(\alpha) - 200}$$

$$r_3 = \frac{-20}{\sin(\alpha)}$$

Figure 7 shows the x and y positions and the velocities of the pin with respect to the angle of the slot plate.

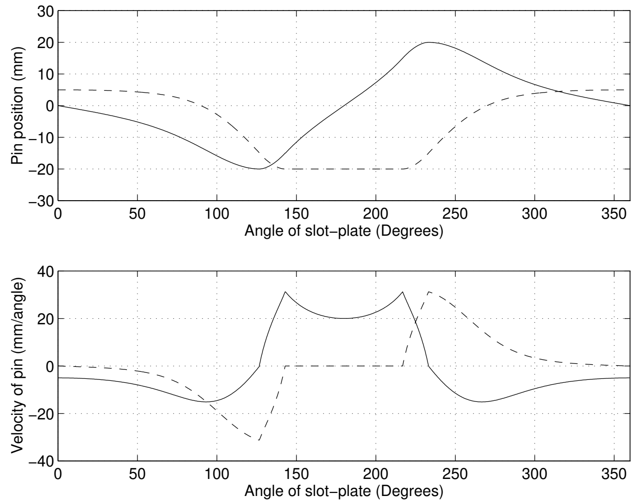

Figure 7: Top: The x (solid line) and y (dashed line) positions of the pin. Bottom: The x (solid line) and y (dashed line) velocities of the pin.

The weight of the leg and the friction in the groove would have a large impact on the velocity of the pin.

Figure 7 therefore shows that the velocity during retraction (143° to 217°) will vary, although only a small amount. This means that the body of the robot will not actually move at a constant velocity and several feet may move at a different speed to the others. In order to overcome this problem, a position control algorithm has been used to retract the robot's legs. A similar algorithm was used for the robot Genghis (Angle 1989) among others.

ADVANTAGES OVER THE BIOLOGICAL MECHANISM

There are several advantages the robot has over the structural design of the cockroach. These advantages are mainly due to the fact that the robot is purely a mechanical system and can therefore overcome some of the problems experienced in a living organism.

As mentioned above, the robot has the advantage of standing without expending energy. Some other advantages are described below.

The legs of the *Blaberus discoidalis* exert vertical forces on the ground of up to 1.5 times it's body weight during a stride (Full et al. 1991). This can cause problems for a machine if no suspension system exists on the legs. These forces are mainly due to the changing gravitational potential energy during walking.

Since the trajectory in the groove is such that the pin will follow a curve prior to entering the retraction section, most of the downward force exerted by the weight of a falling leg will be absorbed by the groove, that is, the leg will not be pounded into the ground. The weight of the robot will not be experienced until the foot is at the same vertical level as the currently standing legs. This means that when the robot is walking, using the tripod gait for example, each foot would not apply any greater force than a third of the robot's body weight while walking on a flat surface.

Also, while walking, the centre of mass of the cockroach experiences repeated horizontal and vertical accelerations and decelerations. The robot would experience much less vertical changes. As mentioned above, the shape of the groove produces the characteristic behaviour of a wheel. Therefore, when the robot walks coherently, a similar changing horizontal acceleration can be expected, as was found in the velocity calculations above. However, since the vertical motion is generally restricted while walking, the gravitational potential energy would be rather constant much like a wheeled vehicle.

CLIMBING OVER OBSTACLES

In (Angle 1991) it was stated that walking and climbing are two very different activities.

When performing a simple walk the foot does not need to be lifted very high off the ground. Strider's feet do however get lifted a reasonable amount during walking and can be thought of as a desirable feature for climbing.

When climbing, the leg needs to be raised higher or lower than for normal walking. This has been accomplished in the robot by adding a vertical actuator at point B in Figure 4. The actuator is comprised of a lead-screw mechanism to produce linear vertical movement of the foot.

The addition of this actuator allows the position of the foot to vary throughout a 95mm vertical distance. Also, with the addition of the maximum height of the groove, the maximum step height will be 195mm.

MAKING THE ROBOT TURN

The main focus of this study is to obtain a faster (straight) walking robot. Making the robot turn is an obvious necessity but was not dealt with to any great extent. Since the legs of this robot do not move in the lateral direction, other methods of turning were required.

Robots such as Genghis (Angle 1989) are made to turn by reducing the retraction length (stride) for the three legs on one side of the robot. Since the stride length using the groove-slot mechanism is constant another method must be used. To make Strider turn, the speed of the retraction can be altered.

In order to make the robot turn towards the right, for example, the right-hand legs must retract slower than the left legs. However, this must only be done when two of the right-hand legs are on the ground otherwise there would be a state where the robot would be standing on only two legs. Some foot slippage will occur but this is almost inevitable for a robot with two degrees-of-freedom per leg.

Various other methods of turning are possible and will be investigated in due course.

PRELIMINARY PERFORMANCE RESULTS

At the time of publication Strider was able to walk at about 14cm/s on flat ground. As expected the legs were not pounded into the ground prior to retraction. Also, as expected, the robot experienced changing horizontal accelerations while walking a tripod gait since there was a small pause between leg movements. This pause however, will be minimised in the near future. The vertical potential energy was almost constant but altered very slightly at each 3-pair leg transition of the tripod gait.

The preliminary results show that the robot does have the potential to produce higher walking speeds.

Work will continue in the near future to examine how the robot performs while walking on an inclined slope, climbing and while turning.

CONCLUSION

A robot named "Strider" was built based on the leg structure of the cockroach. The pantograph mechanism was used for the legs and they were propelled using a unique system known as the groove-slot mechanism.

A comparison of various attributes of the robot with that of the cockroach was given and a description of the groove-slot mechanism was detailed.

The robot can be seen as being a design towards a faster walking robot. The main advantage however, would be the fact that the robot requires no power to stand.

Preliminary results show that Strider was able to walk at 14cm/s at the time of publication, and that the robot has the potential to walk at greater speeds.

From this research it has been found that the inspirations from biological organisms can be beneficial to create some mechanisms in order to reproduce the natural characteristics from those systems. Although, it must be stressed that there is a limit to the amount we can copy these living creatures since we are limited to the mechanics, hardware and actuation devices that we use to build our artificial creatures.

ABOUT THE AUTHOR

Noel Rode is currently working towards his PhD in the Department of Digital Systems in Monash University, Australia. His research covers many areas including mobile robotics, neural networks, control systems, entomology and computer graphics. He completed his Bachelor's Degree in the Department of Robotics and Digital Technology in 1991, and his Honours Degree in 1992 in the same department.

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