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Abstracted Biological Principles Applied with Reduced Actuation Improve Mobility of Legged Vehicles

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Abstract

Applying abstracted biological locomotion principles with reduced actuation can result in an energetic vehicle with greater mobility because a vehicle with the fewest number of motors can have the highest power to mass ratio. One such hexapod robot is Whegs II, which benefits from abstracted cockroach locomotion principles and has just one motor for propulsion. Similar to Whegs I, it nominally runs in a tripod gait and passive mechanisms enable it to adapt its gait to the terrain. One of the drawbacks of Whegs I is that it cannot change its body posture. Cockroaches pitch their bodies up in anticipation of climbing a step to enable their front legs to reach higher. They also flex their bodies down while climbing to permit their front legs to maintain contact with the substrate. A bi-directional servo-driven body flexion joint has been implemented in Whegs II to accomplish both of these behaviors. It is shown to be highly mobile and energetic (see video).

1 Introduction

Engineering problems can be solved using biological inspiration in varying degrees, ranging from a direct implementation to an abstracted one [8]. The problem with the direct implementation of the beneficial attributes of a biological system is that it may require that new technologies first be developed. However, if those same biological principles are abstracted, they may be used to solve problems using currently available technologies.

Cockroaches have remarkable locomotion abilities. Therefore, one solution to the problem of producing mission capable hexapod robots is to design a robot with the mechanisms and control circuits responsible for the mobility of a cockroach. In fact, we have made great progress in doing that [8]. Our Robot V has leg designs based upon the Blaberus cockroach and artificial muscles activate its 24 joints. In preliminary work it has been shown to display passive postural stability and it can move even with no sensor feedback [5]. This robot promises agile dynamic locomotion in the future, but more research is necessary. However, in this process we have learned locomotion principles that can be implemented into robot designs in a more abstract manner using current technology

In studies of cockroach movement, we have noted the following locomotion principles. A cockroach typically walks and runs in a tripod gait where the front and rear legs on one side of the body move in phase with the middle leg on the other side. The front legs swing head-high during normal walking so that many obstacles can be surmounted without significant gait changes. However, the animal's gait can change when it encounters larger barriers. The cockroach turns by generating asymmetrical motor activity in legs on either side of its body as they extend during stance [12]. These actions redirect ground reaction forces to alter the animal's heading [4].

The precursor to the vehicle described in this paper is called Whegs I and its design incorporated the above cockroach locomotion principles [7]. It has a top speed of 5.5 km/hr, or 3 body lengths per second, measured while it moves through a thick lawn. This was at least three times faster than legged vehicles of similar size as reported by Saranli et al. in 2001 [11]. It also climbed barriers that are higher than 1.5 times the length of its legs. However, its climbing capabilities are limited as compared to the cockroach because it cannot change its body posture.

A cockroach enhances its climbing abilities by changing its body posture before and during a climb over an obstacle [13]. It uses its middle legs to pitch its body up prior to climbing obstacles that are higher than its head. This behavior enables its front legs to reach higher. Also, during a climb it uses its body flexion joints to bend the front half of its body down to avoid high centering.

Whegs II (Fig. 1) incorporates a body flexion joint in addition to all of the mechanisms that were implemented in Whegs I. This new actively controlled joint enables it to perform both of the above posture changes used by the cockroach, thereby improving its climbing ability. The most marked improvement as compared to Whegs I is its ability to reach its front legs down to contact the substrate during a climb and to avoid the instability of high-centering.

A comparison of the actuator power to mass ratio of Whegs II with those of other motor driven robots shows that this ratio goes down with an increase in the number of motors. This suggests that a motor driven robot can be more energetic if it has fewer actuators. For this reason previous robots have used reduced actuation. The K2T crab robot used clutches and cables in its drive train so that its 5 motors could drive its 17 joints [2]. Yoneda describes a theory on the subject and several robot designs that have reduced actuation [14]. RHex was developed previous to Whegs and it uses six actuators to drive its six legs [10,11]. Our Whegs vehicles have the fewest propulsion motors possible and they are very energetic.

Figure 1. A top view of Whegs II.

2 Actuation

A legged vehicle that uses only one motor to propel all of its legs has several advantages. For example, all onboard power is available for any single leg that has a foothold. This design also reduces the vehicle's weight. When individual legs or joints are driven by individual motors, each motor must be able to supply the torque needed for the worst case scenario, which results in a heavy robot (see section 9). The one-motor design also eliminates individual control of joints, which simplifies the controller. However, this simplification also limits the possible behaviors of the robots. The drive train and other mechanisms described below reduce some of these limitations.

Whegs I and Whegs II each use a single DC motor to propel all six of their legs. The former is driven by a hobby RC car motor through a custom geared transmission. The latter is propelled by a 90W Maxon motor with an integral 26:1 three-stage planetary transmission, which produces more torque with less frictional losses.

3 Legs

A major advantage of legs over wheels is their ability to gain discontinuous footholds, i.e. they alternate between the stance phase, in which they contact the substrate, and the swing phase, in which they do not. This aspect is beneficial on irregular, discontinuous terrain. The Whegs vehicles' three-spoke appendages, called "whegs" (© R. Quinn, patent pending), abstract the principles of a cockroach's leg cycle while rotating at constant speed. As shown in Fig. 2, this configuration permits the leg to get a foothold on an obstacle that is higher than the length of a spoke.

Figure 2. Whegs I uses three spoke whegs. A three-spoke wheg can reach the top of a barrier that is higher than the length of a spoke.

The whegs are installed on the vehicles such that they form a tripod gait. The front and rear whegs on one side of the body are in phase with the middle wheg on the opposite side to form a tripod. The two tripods are out-of-phase by 60 degrees. When the vehicle walks in a tripod gait on flat terrain, each spoke is in stance during only 60 degrees of its rotation. Therefore, if the spokes are rigid, the hub translates vertically only about 13% of the spoke length or body height. This body movement is less than that of an insect during a typical walk. Radial compliance in each spoke can reduce this vertical translation.

Whegs I has whegs with three 11.4 cm long spokes. The wheg spokes are angled outward 30 degrees from the sagittal plane to give the vehicle a sprawled posture. The feet are made of bent spring steel, which endow the whegs with compliance in the radial direction. Whegs II uses 10cm long spokes that move in the sagittal plane. Each spoke has a spring-loaded prismatic joint, which makes it radially compliant.

4 Steering

Whegs I and Whegs II are each steered by two small RC servos that are electrically coupled to rotate the front and rear whegs in opposite directions. These rotations alter the direction of ground reaction forces of the feet and cause the robot to change its direction of motion. Cockroaches turn in a similar manner; however all three pairs of their legs are engaged in turning their bodies [4].

5 Compliant Axles for Gait Adaptation

The tripod gait is not always suitable for a hexapod. In fact, when climbing larger barriers, cockroaches often move their leg pairs in phase (Fig. 3) [13]. The axles of Whegs I and Whegs II incorporate compliant mechanisms, which accomplish phase changing passively. Inner front, inner middle, and inner rear axles are directly connected to the motor via drive chains. Each inner axle is connected to left and right outer axles via pre-tensioned compliant mechanisms. A large torque on a wheg, during climbing for example, retards the rotation of that wheg. Mechanical stops limit phase change to 60 degrees, at which point the contralateral wheg has moved into phase with the retarded wheg.

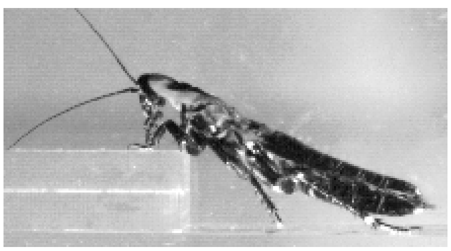

Figure 3. Cockroaches often move their leg pairs in phase while they climb large obstacles.

The compliant mechanisms can improve the climbing ability of a Whegs robot. Consider the situation when the robot approaches a barrier head-on from the left as in Fig. 4. This is a side view, which only shows the front whegs for simplicity. The arrow pointing to the right in Fig. 4A indicates a force applied by the middle and rear whegs that drives the robot toward the right. The force continues throughout this process, but the arrow is not shown in the other stills. In Fig. 4A the right (dark) wheg has just made contact with the obstacle and the front whegs are in their nominal out-of-phase configuration. In Fig. 4B the right wheg axle is complying because of the large external force applied by the barrier on its foot and this wheg is not rotating, but the left (light) wheg continues to rotate. In Fig. 4C this process continues, but the right wheg is sliding up the obstacle because of the force from the middle and rear whegs. In Fig. 4D the left wheg is almost in phase with the right wheg, which continues to slide up the barrier. In Fig. 4E the front whegs are in phase, with their feet on top of the barrier, and the robot has begun to climb. Once the front whegs have surpassed the obstacle, the springs in the axles cause them to move out of phase once again and the robot can return to its nominal tripod gait.

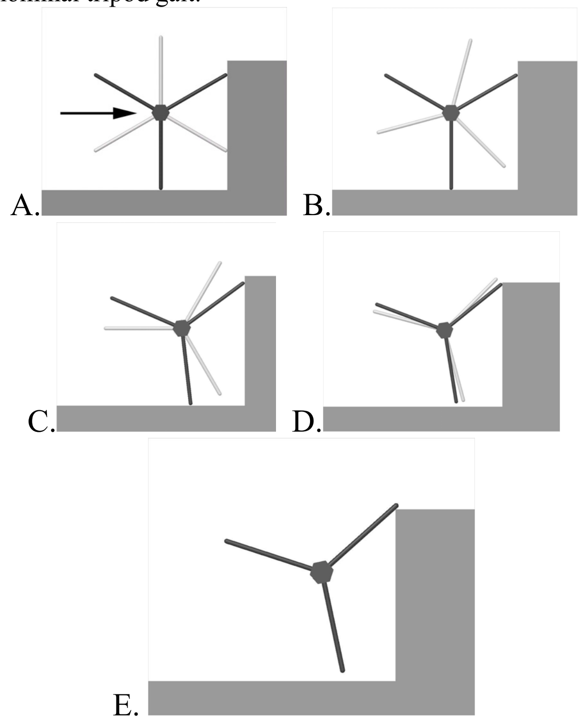

Figure 4: Five stills illustrating how compliant axles can help a Whegs vehicle climb tall barriers.

Both Whegs I and Whegs II have compliant mechanisms in all six of their axles. These mechanisms cause them to run in a nominal tripod gait, but passively adapt their gaits to irregular terrain. This compliance captures much of what the cockroach accomplishes through actions of its distal leg joints. Hence, the vehicle will have more feet in contact with the ground and be more stable. These passive leg adjustments are similar to the preflexes described by Loeb et al. [6].

The compliant axle mechanisms on Whegs II are more compact than those on Whegs I, thereby permitting Whegs II's chassis to be 25% narrower than the Whegs I chassis. This results in a decrease in normalized turning radius from 2.5 body lengths for Whegs I to 1.25 body lengths for Whegs II.

6 Body Flexion

A cockroach enhances its climbing abilities by changing its body posture before and during a climb over an obstacle [13]. For example, it performs a rearing movement prior to climbing obstacles that are taller than it could normally reach with its front legs. To rear up, a cockroach rotates its middle legs so that their extension pitches the front of its body upward, thereby enabling its front legs to reach higher (Fig. 5). A Whegs vehicle cannot rear up using its middle whegs. However, it can accomplish the goal of raising the front legs higher by rotating a body joint upward.

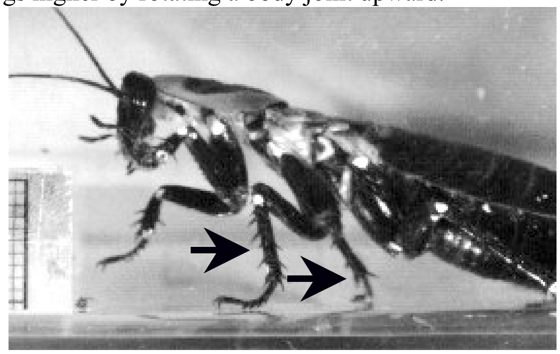

Figure 5. Cockroach rears it body prior to climbing.

Whegs I cannot flex its body or perform the cockroach rearing movement prior to a climb. However, Whegs II has a body flexion joint that is collocated with its middle axle and is actuated by an RC servo. The front of its body can be flexed up (Fig. 6) or down (Fig. 7) 30 degrees from the neutral position. In Fig. 6 it is rearing up the front half of its body so that its front legs can reach the top of a step while the rear and middle legs drive it forward.

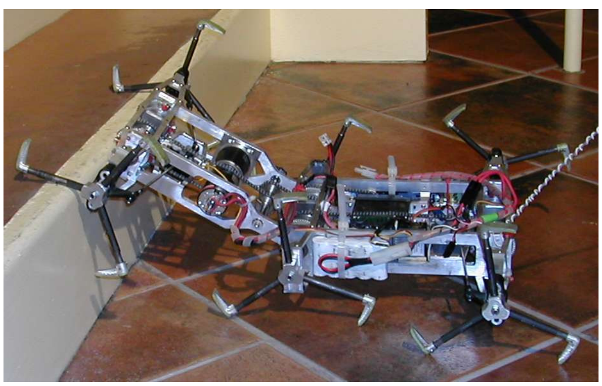

Figure 6. Whegs II rearing the front half of its body.

Cockroaches have a thoracic body flexion joint located between their front and middle leg attachments that enables them to bend the front half of their bodies downward. Fig. 8 (left) shows a cockroach using this joint during a normal climb to bend the front of its body down to avoid high centering. This body flexion enables it to extend its front legs downward and grasp the substrate in a favorable configuration for pulling itself up and over the obstacle. The cockroach in Fig. 8 (right) is performing the same climb with a splint glued to its back that prevents body flexion. It has difficulty grasping the block with its front legs.

Figure 7. Whegs II can flex its body.

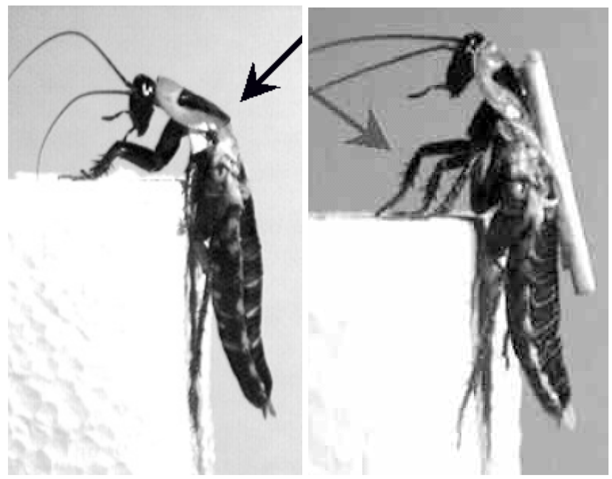

Figure 8. A body flexion joint between the first and second thoracic segments allows the animal to position its legs properly during climbing. On the right prevention of this movement causes high centering.

Whegs I can climb obstacles that are higher than 1.5 times its wheg length despite not having a body flexion joint (Fig. 2). However, when doing so its front whegs lose contact with the ground during the climb (Fig. 9) and it tends to fall to the left or right. Whegs II's body flexion joint enables the front half of its body to be rotated down, which increases its stability by preventing high centering and permitting the front whegs to reach the substrate (Fig. 10).

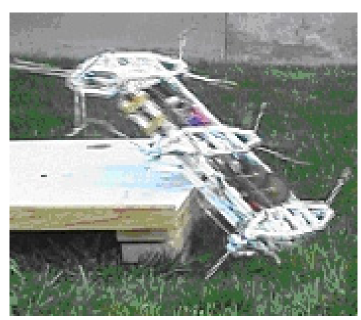

Figure 9. Whegs I cannot flex its body as it climbs.

Figure 10. Whegs II flexing its body as it runs over a curb

7 Results

In summary, the footprint of Whegs II is 47 cm long by 36 cm wide and it weighs 3.86 kg. It has a two-piece aluminum frame and it can flex 30 degrees up and down about its middle axle. It has torsionally compliant devices in all six of its axles. The whegs have internal linear springs (2280N/m) that permit them to comply radially. Its radial wheg-spoke length is 10 cm when no load is applied. It uses a 90-Watt Maxon motor with an integral 26:1 three-stage planetary transmission to propel it, two small hobby servos for steering, and a larger hobby servo to activate the body joint. Its two 7.2 Volt battery packs are placed on its rear body segment such that its center of mass is behind the middle axle and it can lift the front half of its body. Speed, steering and body joint motion are controlled via a hobby RC system. Its original peg feet (Fig. 1) were found to be unsuitable for loosely packed substrates. Curved feet (Fig. 6) improved traction.

Whegs II can run at 3 body-lengths per second. Using its body flexion joint, it can readily climb a series of steps (Fig. 11) that are 1.38 spoke-lengths high and 0.8 body-lengths deep. Whegs II can also run as a quadruped on its middle and rear whegs while holding its front whegs airborne.

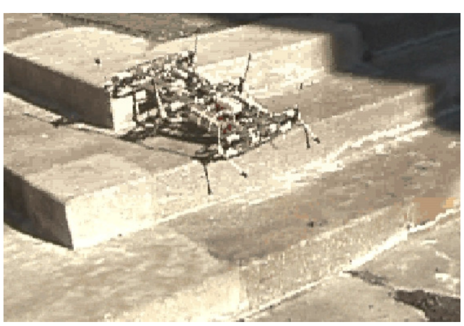

Figure 11. Whegs II climbing stairs.

8 Comparison of RHex and Whegs II

RHex [11] preceded Whegs and a comparison of these vehicles is instructive. Whegs is similar to RHex in that they are both hexapods of similar size that employ single segmented legs, which rotate their feet in a circular path relative to their respective bodies. Both vehicles also benefit from passive radial compliance in their legs. However, there are many differences. RHex uses 6 motors, one to drive each of its legs, whereas Whegs uses just one large motor for propulsion. RHex uses 17.5cm long single spoke legs, so that its control system must accelerate and decelerate each leg during a cycle in order to move its body at a constant speed. Whegs II uses three 10cm long spokes for each leg and its motor runs at a constant speed to move the body at an approximately constant speed. RHex has a software control system that can change its gait for movement over different terrains. The locomotion control system for Whegs is embedded into its mechanics and its torsionally compliant axles permit it to adapt its gait passively to different substrates. RHex turns by skid steering whereas Whegs has two small servos that turn its front and rear whegs for more animal-like steering. Whegs II has a body flexion joint, which RHex does not have.

A comparison of the performance of RHex and Whegs is also interesting. Both vehicles have remarkable climbing and running abilities. For example, they can climb staircases that are higher than 1.3 times the length of one leg. According to Saranli et al. [11] RHex can run at 1 body-length per second and at the time those results were published it was the fastest legged vehicle of its size. Both Whegs I and Whegs II exceed 3 body-lengths per second. In RHex the gait software is changed to accomplish different behaviors such as running or climbing, whereas Whegs passively adapts its gait according to the terrain in real time.

9 Energetics of Motor Driven Robots

Our Whegs vehicles are faster and more energetic than other legged robots of similar size that also use DC motors. For example, Whegs II can accelerate aggressively, causing it to rear up such that its body makes an angle of 30 degrees with the substrate.

Table 1 compares the actuator power to weight ratios of four robots that all use Maxon DC motors with integral transmissions [8]. R-I and R-II are two of our previous robots [1]. The motor power is that rated by the manufacturer and this number can be safely exceeded. However, this is true for all four robots and it would affect the absolute power to weight ratios, but not the trend. Clearly the actuator power to weight ratio increases corresponding to a decrease in the number of gear-motors. This explains the relatively energetic behaviors of Whegs. The trade-off for reducing the number of gear-motors and thereby increasing the power to weight ratio is fewer independent degrees of freedom.

	R-II	R-I	Rhex	Whegs
# motors	18	12	6	1+
W	108	24	120	90
Kg	2.7	0.44	1.8	0.87
W/kg	40	54	67	103

Table 1. Actuator power to mass ratios for robots that use different numbers of DC motors. The motor power is the sum for all propulsion motors onboard. The gear-motor mass includes the mass of all of the motors and transmissions onboard the robot. This value for Whegs II also includes the mass of its servos and drive chains. The values for RHex are from Saranli et al. [11] and Maxon.

10 Conclusions

Abstracted biological principles can be implemented with reduced actuation and current technology to improve the mobility of legged vehicles. Reducing the number of actuators is important because the power/weight of an electric motor driven robot increases with a decrease in the number of its motors. For this reason, the power/weight ratio of Whegs II's actuator system is 50% higher than that of RHex, which was previously the most energetic hexapod. Because of this advantage it can climb at least as well as and run faster than current legged robots. Despite its having only one propulsion motor, it moves in a cockroach-like manner. It passively adapts its gait to different terrain using a "preflexive" locomotion control system embedded in its mechanics. An additional motor is used to implement body posture changes observed in cockroach climbing. An upward rotation of the front half of Whegs II using a body joint effectively abstracts the cockroach's rearing movement prior to a climb. The same body joint directly implements the cockroach's body flexion that helps it avoid high centering during a climb. These postural changes improve Whegs II's climbing abilities by enabling it to reach further upward or downward with its front legs.

Acknowledgements

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