

Comparing Cockroach and Whegs Robot Body Motions

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Abstract

Abstracting cockroach locomotion principles with reduced actuation can lead to a simple yet effective cockroach-like vehicle able to traverse irregular terrain. One such hexapod robot is Whegs VP, which achieves a cockroach-like nominal tripod gait using only a single DC motor. Whegs VP uses compliant mechanisms in its axles to passively adapt its gait to the terrain such that it can climb obstacles of 175% its leg height. High speed video analysis of walking cockroaches and Whegs VP illustrates that Whegs VP walks with cockroach-like body motions. The experiments indicate that stepping patterns play a major role in an animal's or robot's overall body motions.

1 Introduction

Engineering problems can be solved using biological inspiration in varying degrees, from a direct implementation to an abstracted one [10]. Difficulties arise in the direct implementation of biological attributes because oftentimes, the necessary technology has yet to be developed. The design and testing of this technology can be a slow process and ultimately causes its employment to be long-term. However, implementing abstracted biological attributes utilizing existing technology enables mission capable solutions in the near-term.

1.1 Whegs

The Biorobotics group at CWRU takes inspiration from nature when designing and constructing legged robots. In fact, much inspiration has come from studying the cockroach. New mechanisms and control technologies are currently being developed to capture the mobility capabilities of the cockroach. Robot V utilizes leg designs based on the *Blaberus discoidalis* cockroach and uses artificial muscles to activate its 24 joints. In preliminary work it has been shown to display passive postural stability and move with no sensor feedback [5]. This robot's progress is likely to lead to agile, dynamic legged locomotion. Through this process we have learned biological principles can be abstracted and

implemented into mission capable robot designs using current technologies.

The following cockroach locomotion principles are essential to its mobility. A cockroach has six legs, which support and move its body. It 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. The cockroach turns by generating asymmetrical motor activity in legs on either side of its body as they extend during stance [11]. These actions redirect ground reaction forces to alter the animal's heading [4].

Cockroaches have been shown to be excellent sources of inspiration in designing legged robots. Cockroach-inspired robots such as the PROLERO and RHex lines of hexapod robots have shown the usefulness of abstracting biological principles. PROLERO was a hexapod robot designed for the European Space Agency for the purpose of extra-terrestrial exploration [7]. It used reduced actuation (one motor per leg) to power each of its single degree of freedom rotating legs. Similarly, the RHex robot is an untethered, compliant legged robot that travels faster than one body length per second and runs over irregular terrain. It also uses a single spoke leg design and reduced actuation to walk and run [2].

Our first robot designed to use abstracted principles of cockroach locomotion was Whegs I [9]. It has a top speed of 5.5 km/hr (3 body lengths per second) while moving through thick grass. This was at least three times faster than other legged vehicles of similar size [11]. It also climbs barriers that are higher than 1.5 times the length of its legs.

Whegs II (Figure 1), the next generation of Whegs vehicle, incorporates a body flexion joint in addition to all of the mechanisms that were implemented in Whegs I [1]. This actively controlled joint allows the robot to change its posture in a way similar to the cockroach, thus enabling it to climb even higher obstacles. The active body joint also allows the robot to reach its front

legs down to contact the substrate during a climb and to avoid the instability of high-centering. Its aluminum frame and new leg design contributed in making Whegs II more robust than Whegs I.



Figure 1. Whegs II

1.2 Mini-Whegs

A series of small (under 10 cm) novel robots called Mini-Whegs (Figure 2) have also been produced. These highly mobile, robust, and power-autonomous vehicles employ the same abstracted principles as Whegs, but on a scale more similar to the cockroach. These 9cm long robots can run at sustained speeds of over 10 body lengths per second and climb obstacles higher than the length of their legs. One version, called Jumping Mini-Whegs, also has a self-resetting jump mechanism that enables it to surmount obstacles as high as 22cm, such as a stair [8].



Figure 2. Photograph showing relative sizes of the Mini-Whegs IV robot and a *Blaberus giganteus* cockroach

1.3 Motivation

The purpose of this study was to achieve a better understanding of both cockroach body motion and Whegs body motion. Having a numerical description of the animal and the abstracted version's body motions produces two important results. Firstly, an accurate description of the motion would be a useful analytical tool as we continue to try to capture the excellent locomotion capabilities of the cockroach in future robots. Secondly, accurate numerical models of motion allow us to benchmark our current lines of robotic

vehicles against the cockroach. We hope this comparison will lead to performance-enhancing modifications of current robots.

The robot used in this study is a newly constructed Whegs vehicle that is a hybrid of the Whegs I and II vehicles (Figure 3). It was designed to be a fast and reliable vehicle which we could use for a variety of performance-related research. It is most similar in design to Whegs II, but lacks the body flexion joint. It combines the simplicity and agility of Whegs I with the durability and robustness of Whegs II. Improved legs and gait adaptation devices were implemented in the design and will be discussed later.



Figure 3. Whegs VP

2 Whegs Characteristics

The Whegs series of robots employ a design that results in distinct advantages. Among the most noteworthy of these characteristics are actuation, leg design, and gait/gait compliance.

2.1 Actuation

One of the major obstacles in designing legged robots is actuation. A complex actuation scheme results in difficult construction and control. Also, designs requiring complex actuation for each leg result in a heavy robot and poor power-to-weight ratios. Therefore, reduced actuation is desirable. For example, the K2T crab robot used clutches and cables in its drive train so that its 5 motors could drive its 17 joints [3]. RHex and PROLERO, described above, each have only six motors - one for each leg. Their reduced actuation provides them with a distinct advantage over other legged robots.

The Whegs series of robots utilize the simplest actuation scheme possible. Whegs uses only a single motor for the actuation of all its appendages. A legged vehicle that uses only one motor to propel its legs has several advantages. All of the onboard power is available to each leg individually, which is particularly

advantageous if only one foot has a foothold. Also, single motor actuation greatly decreases the robot's weight. The design also eliminates the need to control individual leg joints, thus simplifying overall control. However, this simplification also limits the possible behaviors of the robot. The drive train and other mechanisms described below reduce some of these limitations [1].

2.2 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 the irregular, discontinuous terrain found in most real-world missions. The Whegs vehicles' three-spoke appendages are called "whegs" (© R. Quinn, patent pending) because they combine the advantages of both wheels and legs (Figure 4).



Figure 4. A single wheg

Whegs abstract the principles of a cockroach's leg cycle while rotating continuously at constant speed. They 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. If the vehicle walks in a tripod gait on flat terrain, each spoke will be in stance during only 60 degrees of its rotation. Therefore, even if the spokes were rigid, the hub would translate 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 [1].

2.3 Compliant Axles for Gait Adaptation

A tripod gait is not always useful for a hexapod. Sometimes, the terrain or obstacles dictate a change in gait. In fact, when climbing larger barriers cockroaches often move their legs in phase [14].



Figure 5. Like the cockroach, Whegs brings its legs into phase to climb obstacles.

All Whegs vehicles have compliant mechanisms in their axles which accomplish this passively. The inner front, inner middle, and inner rear axles are directly connected to the motor via drive chains. The inner axles are connected to left and right outer axles via six compliant mechanisms. These compliant mechanisms greatly improve the climbing ability of the vehicle. Consider the climbing example shown below. A large torque on a front wheg, caused by contact with an obstacle, retards the rotation of the wheg while allowing all other whegs to continue rotating in their nominal out-of-phase configuration. Mechanical stops in the compliant mechanism limit the retardation to 60 degrees, at which point the contralateral wheg has moved into phase with it. Now that both whegs have come in contact with the obstacle, the vehicle can hoist itself up and over. Once the front whegs have cleared the obstacle, the compliant mechanisms cause the whegs to move back out of phase and the robot can return to its tripod gait.

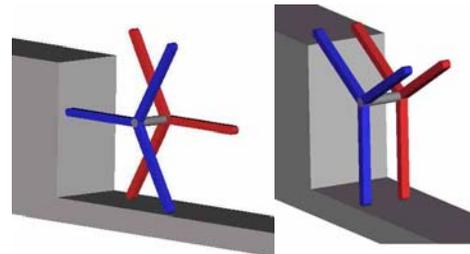


Figure 6. Compliant mechanisms in the axles allow wheg spokes to come into phase and climb obstacles

The compliant mechanisms found in all Whegs vehicles 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 with actions of its distal leg joints. Therefore, the vehicle will have more feet in contact with the ground and be more stable [1].

3 Improved Legs

Whegs I used our first design for three-spoked appendages. These simple appendages had solid metal spokes and spring steel feet. These whegs were

effective. However, they occasionally could not grip terrain and their rigid design resulted in a rough ride. These problems led to a new design. Whlegs II used new whlegs as shown in Figure 4. This design introduced spring-loaded, telescoping spokes to reduce impact and vibration. New feet with rubber soles were also added. These whlegs were successful; but an even more robust line of whlegs have been designed to improve walking and climbing.

3.1 Design and Construction

The goals for the new whleg design were improved flexibility/compliance and mechanical simplicity. The Whlegs II appendages were an improvement on the previous whleg design, but still did not provide the desired flexibility when traversing irregular terrain. They also consisted of many parts, resulting in large assembly times and greater wear-and-tear. Therefore, a one-piece, flexible spoke was constructed (Figure 7).



Figure 7. A new whleg

The new spokes were designed wider and with a longer 'foot' area to provide a larger and more stable foothold on terrain. Treads were incorporated on the outer surfaces to aid in traction and climbing. A large heel claw was added to help climb large obstacles. Spring steel was chosen as the skeleton of the spoke to provide strength and flexibility. The body of the spoke consists of a flexible yet durable urethane compound with stiffness comparable to the rubber sole of a tennis shoe. After some initial testing, it was decided that the new whleg design required additional damping. As such, some visco-elastic material was mounted on the inside curve of each spoke to provide the necessary damping.

Thin strips of spring steel were cut and manually shaped to form the inside skeleton of the spoke. The spring steel was then placed in a Delrin mold in which the two-part urethane was poured and cured. Because all previous whlegs parts were manufactured in-house and also required a large amount of post-process machining, overall construction time of the new whlegs is an improvement over previous designs. Also, the new

whlegs are considerably more durable and require less maintenance time.

3.2 New Design Performance

The new whleg design resulted in greater traction and climbing abilities. Whlegs VP was able to travel over slippery surfaces that it could not previously traverse well. The vehicle equipped with the new whlegs never failed to climb an obstacle (a cardboard box) of 7 inches, 1.75 times the leg height (Figure 8). Traction on the footpad area of the whleg allowed the vehicle to propel itself upward, then the heel claw would catch on the obstacle. The aforementioned torsional compliance mechanisms allowed both whlegs to come in contact with the obstacle, which enabled the robot to pull itself up and over the obstacle.

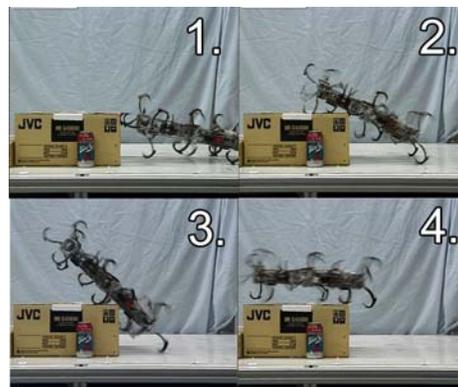


Figure 8. Whlegs VP climbs a 7 in obstacle

4 Results

4.1 Cockroach Body Motion

Cockroaches from the Ritzmann Lab at CWRU were videotaped using high-speed video to capture body movements while walking (about 1 to 1.5 body lengths per second) on a treadmill. Front, side, and ventral views were captured simultaneously. Tracking dots were placed on the cockroach at significant places and tracked using the WINalyze[®] video tracking software.

Twenty video segments from 7 cockroaches were taken. Four cockroach video segments made it through a rigorous screening process and were analyzed. Two of the four cockroach body motion data sets were the most regular and representative and are presented. Because of the relatively small sample size, the cockroach body motion experiments cannot provide a definitive generalization of how all cockroaches move. However,

the data does provide a good platform for comparison between cockroach and robot body motions.

Considerable overlap time was found between the stance periods of the alternate tripods. The overlap period results in all six legs on the ground and occasionally lasted as long as single-tripod stance periods, especially at slower speeds. While the cockroach motion was quite variable; certain trends did appear. A strong correlation was found between the cockroach's stepping pattern and its body rotations.

Among the most regular of body movements was the cockroach body roll motion. Both cockroaches generally exhibited one roll motion of about ± 7 degrees with each step. The animal started a roll motion rolled toward the side of the body with two legs (front and rear) in contact with the ground. The cockroach obtained a neutral roll angle as it continued to roll toward the opposite side with one leg (middle leg). As the stance is transferred from one tripod to the other, the cockroach continued to roll toward the opposite side with two legs newly in contact with the ground.

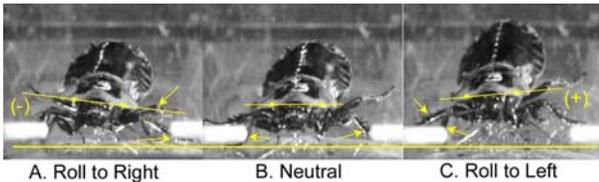


Figure 9. Cockroach rolls from one side to the other with each step. Arrows point to legs on the ground.

The animal's pitching motions were less regular but still exhibited general trends. The cockroaches tended to pitch up and down with each step. The pitch rotations therefore occur at twice the frequency of roll motions. Each cockroach had its own natural walking attitude. Some cockroaches walked pitched down, some pitched up. The animal starts its pitch motion at the natural attitude and pitches up as the stance tripod moves through its stance phase. The cockroach pitches back down to its neutral attitude as the next tripod enters its stance phase. These pitch motions were generally ± 4 degrees.

Least regular of the cockroach body motions was the center of mass position. As expected, significant changes in center of mass position occur with a transition between stance tripods. CoM oscillations of about ± 10 -15% of the animal's nominal height were common. However, no concrete trend in the magnitude or frequency of those movements could be claimed.

4.2 Whlegs Body Motion

Robot body motions were captured in a similar manner as the cockroach. High-speed video of the robot walking on a treadmill (around 1 body length per second) was taken and digitized. The WINalyze[®] software was again used to track body motions. Front and side view videos were taken separately due to equipment restrictions.

Whlegs VP takes shorter steps and has a much shorter overlap phase than the cockroach. It generally has cyclic body motions due to its mechanical nature. Some variability in the data was encountered due to bouncing (caused by compliant legs) and inconsistencies in the vehicle velocity. However, definite trends in body motions were found.

Robot roll motions (blue data below) occurred at a similar frequency as cockroach roll motions. The data was somewhat wavy, but the robot exhibited one roll motion (one side to the other) per step. These roll motions were about ± 2 degrees, smaller than cockroach roll motions.

Also like the cockroach, the robot's tripod gait resulted in an up and down pitching motion (red data below) with each step. The robot pitch magnitudes were about ± 2 degrees. A casual look at the body motion graph shows that the pitch and roll motions occur at the same frequency. However, a closer look reveals that an up and down motion does occur with each step. A much smaller magnitude pitch motion occurs in between large pitch motions. The small pitches may be attributed to inconsistencies in leg phasing which caused the robot to favor one side.

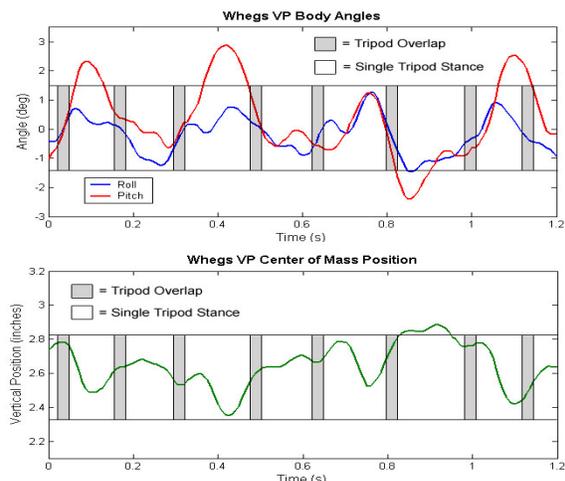


Figure 10. Whlegs VP body motions. Overlap phase is denoted by a grey rectangle.

Robot center of mass motions (green data above) were 'm'-shaped and somewhat regular. The local peaks and valleys of the sinusoidal motion usually corresponded to a single tripod stance, but the frequency of the transitions was rarely constant. CoM oscillations were about $\pm 9\%$ of the nominal position.

5 Conclusions

The roll and pitch motions observed in cockroaches agrees with the qualitative results published by Kram [6] and Ting [12]. It has been experimentally shown that Whigs VP exhibits similar roll and pitch motions to those of the cockroach. The greatest difference between Whigs VP and its cockroach inspiration is the magnitude of the body motions. Whigs VP has significantly smaller body rotations than the cockroach. This may be attributed to the robot's relatively small step size as compared to the cockroach.

Conversely, robot center of mass motion is similar to the cockroach in magnitude (around $\pm 10\%$ about a nominal height) but not in shape. Whereas the cockroach oscillations are sinusoidal, Whigs VP's CoM oscillations are 'm'-shaped and similar to the inverted pendulum pattern exhibited by bipedal walkers. However, both robot and cockroach center of mass motions show a dependence on step pattern.

Whigs VP's design abstractly captures cockroach locomotion capabilities and results in cockroach-like body motions. The robot also passively adapts its gait to help traverse irregular terrain and climb obstacles in a manner similar to the cockroach. Whigs VP has legs of a significantly different scale (with respect to its body) than the cockroach. Nevertheless, the body motion experiments show that the robot exhibits body motions with a similar pattern as the cockroach. This suggests that body motion patterns are rooted in the tripod gait stepping pattern.

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