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Improved Mobility Through Abstracted Biological Principles

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Abstract

Biological inspiration can be used to improve the mobility of vehicles, even those that are simplified and use current technology. One such hexapod robot called Whegs I is described. Mechanisms in its design permit it to move over various terrains and climb over small obstacles in a manner similar to a cockroach. It uses one motor for propulsion and two small servos for steering. Its appendages, called whegs, consist of three evenly spaced spokes. Passive compliance in its axles permits its nominal tripod gait to adapt to irregular terrain and evolve to co-activation for climbing. Basic locomotion control is implemented in its mechanical design. A benefit of this mechanical simplicity is that its control system is also simplified. Drawbacks to the simplifications include the inability to change the body's posture and decrease overhead clearance. Some of these problems will be addressed in future versions without compromising the basic design.

1 Introduction

Problems in robotics can often be solved through intelligent biological inspiration [9]. In fact, biological inspiration can be used in varying degrees depending upon the scope of the work. A longer time frame permits the development of technologies needed to implement more of the beneficial attributes of a biological system. However, if the biological principles are abstracted, they can be used to solve problems in near term vehicles using current 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. Our Robot III, with leg designs based upon the Blaberus cockroach, has been shown to have postural stability and to cycle its legs in a cockroach-like manner [6,7]. However, there remain design and control issues yet to be solved. Hence, it is a far-term solution to the problem that will ultimately reap great rewards. The question then is what have we learned in this process that can be implemented into mission capable robots now?

This paper describes a simplified vehicle called Whegs I whose design was inspired by abstracted locomotion principles extracted from studies of cockroaches. 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 a change in gait. However, its gait changes when it encounters large barriers. The cockroach pitches its body up prior to climbing large obstacles and uses its body joints to avoid high centering during a climb [14]. The cockroach turns by generating asymmetrical motor activity in legs on either side of its body as they extend during stance [13]. These actions redirect ground reaction forces to alter the animal's heading [5].

Whegs I has only one drive motor, yet it moves quickly and climbs obstacles using all of these cockroach strategies with the exception of the body flexion joint. Whereas only one large drive motor is used, small servos steer the vehicle. These simplifications are possible because much of the vehicle's control is imbedded in passive mechanical systems. The two most important of these components are appendages that we call "whegs" (© R. Quinn) because they have some of the advantages of both wheels and legs and compliant devices in the drive train (patent pending).

Previous robots have used reduced actuation to limit their weight and increase their payloads. The K2T crab robot used clutches and cables in its drive train so that its 5 motors could drive its 17 joints [3]. Yoneda describes a theory on the subject and several robot designs that have reduced actuation [16]. RHex is a current hexapod vehicle that uses reduced actuation for the same reason [12]. Each of its legs is driven by just one DC motor and each foot moves in a circular path relative to the body. Each leg is accelerated through its swing phase so that the tripod and other insect gaits are possible. Whegs I was designed with even fewer actuators because we wished to increase its payload and simplify its control.

2 Actuation

Actuators are the components that most limit the performance of legged vehicles, complicate their control, and increase their cost. Electric motors are easy to control, but their power to weight ratio is poor as compared to muscle. The weight of the gear-motors on a hexapod such as Robot II or TUM, with three motors per leg, may account for as much as 60% of the total weight of the vehicle [2, 15]. This is true despite the fact that these two robots used gear-motors with the best power/weight ratio available at the time they were designed. For multi-segmented legs an actuator is needed that exhibits power to weight, structural flexibility, reliability, and tunable passive stiffness similar to muscle. We are implementing one such "artificial muscle" in Robot IV [10] but, more research needs to be done to improve this technology and, therefore, this is a long-term solution.

To solve this problem, Whegs I uses a single conventional electric motor to propel itself. Because gear-motors are one of the most massive components on an electrically-actuated legged vehicle, this design greatly reduces the weight and increases the payload capacity. Furthermore, when one leg encounters an obstacle and the other legs are slipping, the single leg with a solid foothold requires a great amount of torque to propel the robot. In this one drive-motor design, all of the motor's torque is available for that leg. When individual legs or joints are driven by individual motors, each motor must be powerful enough for the worst case scenario. This requirement results in large, heavy motors. The motor for the single-motor robot design can weigh much less than the combined weight of all of the motors on a robot with legs or joints driven by individual motors. This weight savings makes up for the additional weight of the drive train that delivers the torque to the legs. The one-motor design also eliminates individual control of joints, which simplifies the controller. Of course this simplification reduces the possible behaviors that the robot can perform. The drive train and other mechanisms described below reduce some of these limitations.

3 Leg Design

An efficient leg supports and propels the body during its stance phase and then rapidly returns to again support the body. A single leg rotating continuously as used in RHex must change speed between stance and swing to accomplish this kind of movement [12]. A simple control circuit is required to perform this acceleration of each leg. However, the principles of the leg cycle can be accomplished with an appendage that we call a "wheg", which is made of three flexible spokes symmetrically distributed about a hub so that they are separated by 120 degrees. The desired leg cycle motion is accomplished with this appendage driven at constant speed continuously over its full 360 degrees of rotation. As shown in figure 1A, this configuration permits the leg to get a foothold on an obstacle that is higher than the length of a spoke. If the motor and leg are strong enough, then the leg can drive the robot over such an obstacle. This design is greatly superior to the climbing ability of a conventional wheel, as shown in figure 1B, where the wheel's radius is comparable to the length of one spoke of the wheg. Although the addition of knobby tires or treads can increase traction, they cannot overcome this fundamental limitation of wheels.

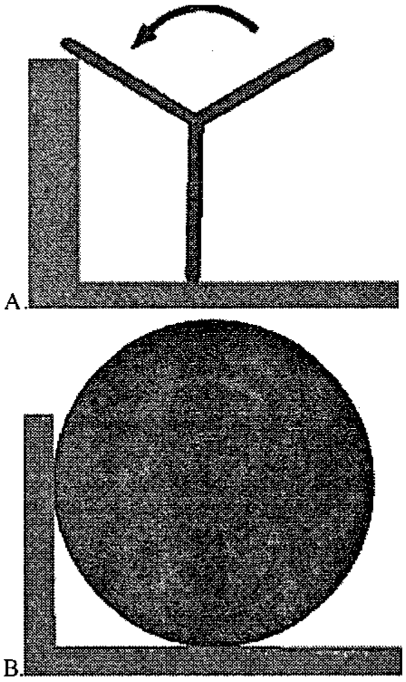

Figure 1. A three-spoke wheg (A) can reach the top of a barrier that is higher than the length of a spoke. A wheel (B) can not do this.

Given that the goal is for the motor to run at a constant speed to drive the robot forward at nearly a constant speed, a three-spoke wheg is a compromise between climbing capability and ride smoothness. A two-spoke wheg would have better climbing abilities (Fig. 2A), but walking would be difficult. A four-spoke wheg would be less capable for climbing steps (Fig. 2B), but would provide a smoother ride. As shown in Fig. 1A, the three-spoke wheg has good potential for climbing. The ride smoothness is also acceptable as discussed below.

At first glance, it would appear that a wheg with three spokes would provide a very rough ride on smooth terrain. However, if the hexapod walks in a tripod gait on flat terrain, each spoke will be in stance during only 60 degrees of its rotation. During the next 60 degrees, spokes on the adjacent whegs will support the body. This property is demonstrated in figure 3. When the dark gray wheg is vertical and supporting the body, the hub is at its highest position. When the light gray wheg next contacts the ground, both whegs have rotated 30 degrees. Therefore, if the spokes were rigid, the hub would translate vertically according to

$$\text{Change in hub height} = \text{spoke length} * [1 - \text{cosine } (30^\circ)]$$

or about 13% of the spoke length or body height. This percentage of body height movement is less than that of an insect during a typical walk. Leg compliance can reduce this vertical movement further.

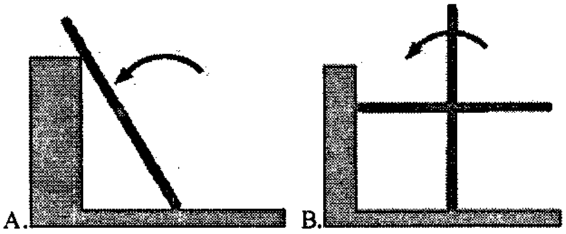

***Figure 2**. The two-spoke wheg (A) has a greater potential for climbing, but is not suitable for walking. The four-spoke wheg (B) would provide a smoother ride, but can not reach higher than its hub.*

Another advantage to using the three-spoke whegs is that the robot could continue moving despite the loss of a spoke. The ride would be less smooth, but the robot could continue walking.

The biomechanics of legged animals suggest enhancements to the above configuration. First, animal legs are compliant and the resulting energy efficiency allows them to walk for much longer periods of time than if their legs were rigid [1]. This is not a new idea in robotics; one of our previous hexapods, Robot II [2], RHex [12], and various bipeds by Pratt [8] all have passive compliance built into their legs. However, animals have the advantage of being able to change their muscle stiffness, and thereby their leg compliance so that they can walk efficiently at different speeds. We are solving this problem in our robots with multi-segmented legs. For simplicity, our whegs use springs of constant stiffness. If each spoke can flex lengthwise as shown in figure 4, the spoke may flex during the first 30 degrees of stance and extend during the second 30 degrees. This can smooth the body's vertical motion and potentially provide increased energy efficiency at one particular speed of the vehicle.

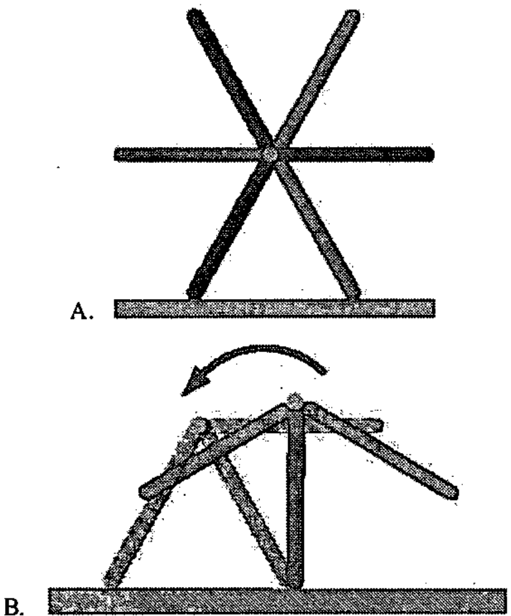

***Figure 3**. A pair of three-spoke whegs. The robot is moving to the left. The lighter gray tri-spoke wheg is on the opposite side of the body. Note that there is a 60 degree separation between the spokes when the whegs are out-of-phase as is the case when the robot is in a tripod gait. (A) As the robot moves to the left, the light gray wheg is ending its support phase and the darker gray wheg is beginning its support phase. (B) The height of the hub drops only 13% during this transition.*

4 Compliant Axles for Gait Adaptation

The front legs of cockroaches are important in climbing because they reach in front of the body and find footholds on top of obstacles. Behavioral studies indicate that if a cockroach can reach its front legs on top of a barrier, it can climb that obstacle. In fact, cockroaches normally lift their front legs head-high during the swing phase so they can run over many obstacles (about 3/4 nose height) without making any changes to their gait pattern (Fig. 5A) [11]. If the front axle is placed far forward on the body, the three-spoke configuration is a good one because the spokes can reach forward on top of upcoming obstacles (Fig 1A). Making the three-spoke wheg flexible also benefits the front legs because when a spoke is in its swing phase, it is unloaded and at its greatest length. Therefore, it can reach forward farther.

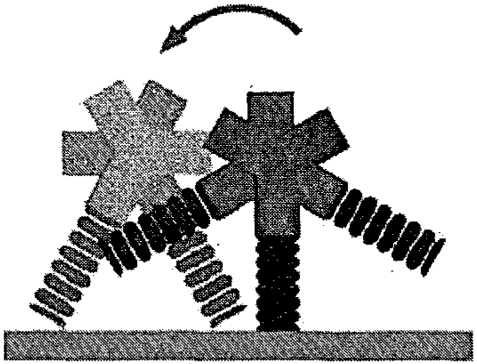

***Figure 4**. The spokes of the tri-spoke wheg are compliant. Some of the spokes are not shown for clarity. The dark gray spoke is compressed the most by the weight of the body when the spoke is vertical. As it rotates 30 degrees to finish its stance phase, the spring is decompressed and the change in the height of the hub is less than if the legs were rigid. Furthermore, the energy released from the spring results in a forward push on the robot, which then compresses the light gray spoke on the opposite side of the body.*

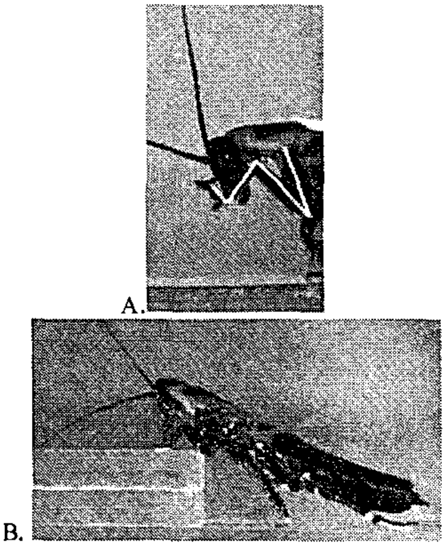

***Figure 5**. (A) Cockroaches raise their front legs high during normal walking so that they can climb over small barriers without changing their gait. (B) The pairs of legs often move in phase while they climb large obstacles.*

For larger barriers, cockroaches often move their leg pairs in phase (Fig. 5B) [14]. The compliant axles of Whegs I can accomplish this passively. Consider the situation when the front whegs of a robot approach a step barrier head-on as shown in Fig. 6A. This view shows the pair of three-spoke front whegs out-of-phase as in a tripod gait. The left wheg is dark gray and the right wheg is shown in light gray. A spoke of the left leg strikes the barrier before the right leg reaches the top of the obstacle. This problem could greatly reduce the maximum height of a barrier that can be climbed, but it can be overcome with the incorporation of torsional compliance in each of the axles. In this case, both whegs continue to turn and the right wheg reaches the top of the obstacle. The right wheg then remains in this orientation because its axle complies and the left wheg is driven into phase with the right wheg. In figure 6B the front whegs are in-phase and the robot can climb the obstacle. Once the front whegs have surpassed the obstacle, the springs in the axles cause the whegs to move out of phase once again and the robot continues to walk in a nominal tripod gait.

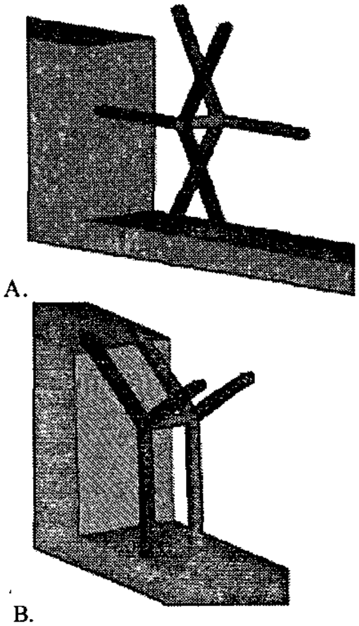

***Figure 6**. (A) The left front leg (dark) strikes the obstacle and prevents the right front leg (light) from reaching the barrier. (B) The compliant axles permit the front legs to move in phase and the robot can climb the obstacle.*

If torsional compliance is implemented in all six axles, an additional benefit can result. Although the vehicle will walk in a nominal tripod gait, its gait will adapt to irregular terrain because of these compliant mechanisms. Hence, the vehicle will have more whegs in contact with the ground and be more stable.

5 Middle and Rear Legs

During normal walking, the middle legs of the cockroach support the weight of the body and alternately accelerate and decelerate the body during stance [4]. The three-spoke wheg design is a good abstraction for the middle legs, because they will perform these functions. The powerful rear legs of a cockroach propel it forward. The foot moves along a line parallel to the body and in normal walking the foot remains behind the body joint. The three-spoke wheg design used as a rear leg can propel the body forward, but it will not perform this function in the manner of a cockroach rear leg.

6 Steering Mechanism

Insects redirect lateral forces during turning [5]. This can be accomplished with steering mechanisms like those found in automobiles. If the front whegs are turned to the right, they will pull the body to the right and steer the vehicle. If this is the only mechanism used for steering, the middle and/or rear legs must slip or bend for turning to take place. To avoid this and to enable turns of shorter radius, the rear whegs steer in the opposite direction of the front whegs. The interference of the whegs with the body as they are turned limits the radius of the turn. Given the track of the vehicle (distance between whegs across the body), this turning consideration limits the width of the chassis at the front and rear of the vehicle.

7 Whegs I

We have developed a hexapod vehicle that benefits from the abstracted biological principles described above. It uses three-spoke whegs for all six of its appendages. This vehicle is shown in figure 7 and is called Whegs I. It has a single drive motor and two small servo motors for steering. The biological principles that are incorporated into its design include a nominal tripod gait that passively changes on irregular terrain and evolves into co-activation of legs for climbing. It also has the capacity to place its legs on top of large objects for climbing.

Whegs I is 50 cm long and 50 cm wide. All six whegs have 11.4 cm long spokes. The wheg spokes are angled away from the vertical at 30 degrees. Spring steel 0.635mm thick was bent to form compliant feet. It uses an RC car motor and steering servos. It carries a 7.2 volt Ni-CAD battery and its speed and steering are controlled remotely. When Whegs I's drive motor runs at a constant speed the vehicle moves at a constant speed. Its top speed is about 5.5 km/hr or 3 body lengths per second measured while it moved through a thick lawn.

Steering the Whegs robot is accomplished by rotating the front and rear whegs. This alters the placement of the feet and causes the robot to steer, which is also how the cockroach turns. Whegs I has a turning radius of 4 ft. This large radius is caused by interference in the mechanisms. The turning radius of subsequent models can be greatly reduced through more careful design.

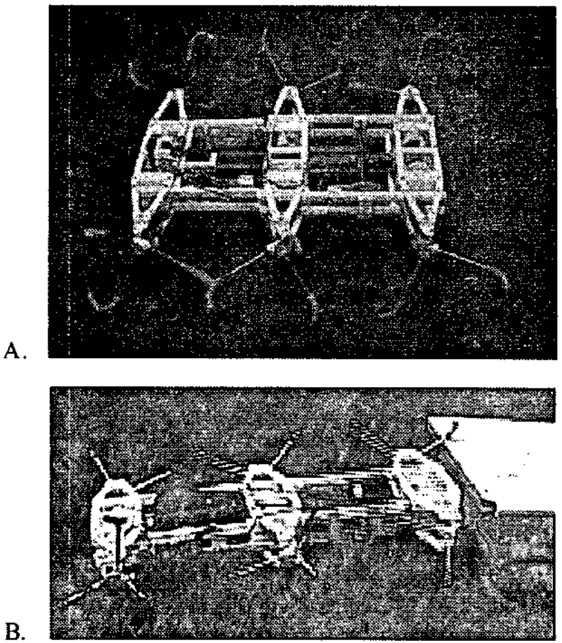

Figure 7. *(A) Whegs uses tri-spoke appendages. (B) Whegs climbing a 15cm obstacle with its front and middle whegs in phase.*

Like the cockroach, the hexapod Whegs I can climb small barriers without changing its nominal tripod gait. We incorporated passive torsional compliance into the axles of all six whegs. When a large obstacle is encountered the whegs passively move into phase from their nominal out-of-phase tripod gait (Fig. 7B). Results of this compliance are that the robot passively changes its gait as it walks over natural terrain and its climbing ability is enhanced. It has been shown to climb a rectangular obstacle with a height of greater than 1.5 times the wheg radius (Fig. 7B). Furthermore, at high speed on relatively level terrain the vehicle uses the tripod gait and moves with little vertical body motion. These gait adaptations are entirely due to passive mechanisms and the only control inputs are speed and direction.

To our knowledge Whegs I is faster than any legged vehicle of similar size and it can climb higher barriers than wheeled vehicles of similar size. However, there are drawbacks to the design of a vehicle with these simplifications. The three-spoke design has the disadvantage of raising the minimum height of a barrier that the robot can crawl underneath. Another concern is that the multiple spokes on a single wheg can become tangled in certain terrain. Furthermore, the vehicle cannot change its body posture whereas insects make good use of this feature in climbing and burrowing. We will address some of these concerns in later simplified vehicles. Note that robots, which are more like animals and have segmented legs, can easily avoid these drawbacks.

8 Conclusions

Abstracted biological principles can be implemented in the near-term to improve the mobility of vehicles. A new hexapod called Whegs I benefits from cockroach locomotory mechanisms. It nominally walks in a tripod gait, but its gait passively adapts to irregular terrain and evolves into co-activation of legs when climbing large obstacles. Also, like the cockroach, its front appendages reach high in front of the vehicle so that it can climb smaller obstacles without changing its gait. It performs these cockroach locomotion tasks while using only one motor for propulsion and two small servos for steering. One innovation is the design of its appendages called whegs that are a hybrid of wheels and legs. The three-spoke wheg design is a compromise between the desire for a smooth ride and obstacle climbing ability. The benefits of Whegs I's one drive-motor design are that the maximum onboard torque can be delivered to any leg, which reduces the chance of stall, and the vehicle can have equal climbing abilities with less overall motor weight and greater payload capacity. Whegs I can move at a top speed of three body lengths per second because of these innovations. Another important innovation is the torsional compliance in the axles, which permits the vehicle's gait to passively adapt to irregular terrain. Using this mechanism Whegs I was shown to climb rectangular obstacles that are 1.5 times the height of the wheg radius.

Acknowledgements

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