Mechanized Cockroach Footpaths Enable Cockroach-like Mobility

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Abstract

Implementing cockroach footpaths using simple leg mechanisms results in cockroach-like body motion in a hexapod robot called "MechaRoach." MechaRoach utilizes rotary input four-bar mechanisms to achieve legged locomotion while being powered by only one DC motor. MechaRoach can walk at one body length per second and can climb a barrier 70% its height. High speed video analysis of walking cockroaches and MechaRoach indicates that MechaRoach exhibits body motion during walking that is very similar to the cockroach. This suggests that footpaths and stepping patterns play a significant role in an animal or robot's overall body motion.

1.0 Introduction

Biological inspiration can provide a host of effective solutions to complex engineering problems. The strategies for the implementation of biological principles can range from direct to abstract. The direct approach attempts to mimic the complex neuromechanics found in biological systems, and therefore often requires the development of new technologies. However, to avoid this added complexity, the beneficial attributes of the biological system may be abstracted, permitting a near-term implementation of an engineering solution that benefits from biological inspiration.

Legged robots have been created that benefit from abstracted biological principles. MIT's Boadicea was one of the first robots to mechanically mimic cockroach footpaths, resulting in a 16 degree of freedom tethered robot that could walk and climb [1]. The PROLERO robot further abstracted cockroach foot motion by implementing a single rotating spoke design for each of its six legs. PROLERO's legs were articulated to permit walking, turning, and climbing modes by controlling the way each leg swings in and out of stance [8]. RHex expands upon the single spoke concept by incorporating compliant legs and more complex control architecture [12]. RHex exhibits a wide range of behaviors while being powered by only six motors.

Cockroaches provide an excellent model for the development of agile legged robots. Cockroaches exhibit remarkable locomotion capabilities across a variety of terrain. In an attempt to capture the wide-ranging mobility of the cockroach, our Biorobotics Lab is currently developing Robot V, a 24 degree of freedom hexapod robot [6]. Robot V's legs are designed and controlled based upon the *Blaberus discoidalis* cockroach, using artificial muscle to articulate each of its joints in a manner directly inspired by the cockroach. By doing this, we hope to soon develop the control and actuation strategies necessary to achieve agile, dynamic locomotion. However, current technology does not yet permit the complete implementation of this solution.

The abstracted approach, however, does permit immediate implementation of mission capable robots. Certain ingredients essential to the cockroach's mobility may be abstracted into robot designs using current technologies [10]. Cockroaches walk and run in an alternating tripod gait in which the front and rear legs on one side of the insect's body walk in phase with the middle leg on the opposite side. This creates two sets of stable tripods that alternate between stance and swing, permitting a stable, yet rapid gait. Cockroaches also nominally swing their front legs head-high, allowing them to surmount small obstacles without significant gait changes. When encountering a relatively large obstacle, the cockroach adjusts its gait by bringing contralateral legs into phase with one another, allowing it to exert more force to surmount the barrier [15]. Simple mechanics such as these provide a good model for the development of near-term robots.

Our lab has been developing the Whegs series of robots, which draw upon the simple, but effective methods that the cockroach uses to traverse rough terrain [9]. Whegs are hexapod robots that use a three-spoke rimless wheel called a "wheg" (© R. Quinn, patent pending) to achieve legged locomotion. They walk in a nominal tripod gait and use spring-loaded torsional compliance devices to allow coaxial legs to shift in and out of phase. A single motor actuates all six whegs, with power transmitted via chains and sprockets. The Whegs series of robots have been shown to run at 3 body lengths per second and climb obstacles over 1.5 times their hip height. These robots are energetic, robust, and may be immediately implemented to perform real world missions.

Many of Whegs' successes may be attributed to its biological inspiration, but its highly abstracted design has several drawbacks. For example, each wheg must swing up over the top of the robot before reaching stance. This means that however thin the robot's body may be, its overall height will always be at least twice its leg length. This limits Whegs' ability to walk under low overhangs. Cockroaches, on the other hand, lift their legs only as high (at most) as the top of their body. Also, each set of the cockroach's legs is specialized to perform a series of locomotive tasks. All three sets of whegs, however, are identical, limiting the diversity of Whegs' capabilities.

Each pair of the cockroach's legs is used in a different way. The cockroach's front legs swing head-high, in order to climb small obstacles without active gait adjustment. The middle legs carry much of the insect's weight, and move in such a way that they alternately accelerate and decelerate the body. The powerful rear legs push in a linear, almost piston-like manner, propelling the cockroach forward. The cockroach's rear legs also project from its rear, which provides resistance to rearward tipping during climbing [15]. These specialized leg functions are key to the remarkable agility of the cockroach; so we expect that implementing them in a robot design may lead to highly mobile and robust locomotion.

This paper describes a new robot, MechaRoach, whose legs are articulated mechanisms designed to perform the specialized tasks of the cockroach's legs. MechaRoach (Fig. 1) is propelled by a single drive motor and is capable of walking at one body length per second and climbing obstacles up to 70% of its body height. It weighs 7.75 lbs and its body is 11 in. wide, 18 in. long and stands 7 in. tall. Beyond a superficial resemblance to the cockroach, MechaRoach exhibits cockroach-like foot and body motions, which has been demonstrated experimentally.

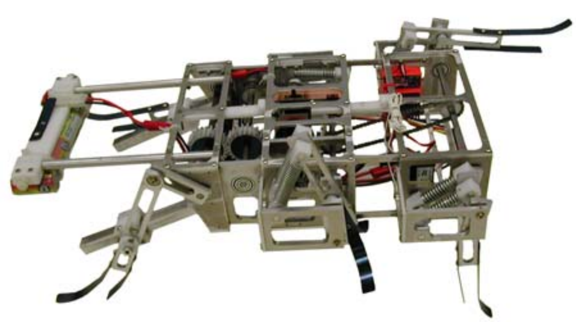

Fig. 1. A top view of MechaRoach

2.0 Robot design

MechaRoach's legs are designed such that the path that the robot's foot follows during one stance/swing phase mimics that of the cockroach. While the joints that are articulated to perform this task differ from the morphology of the cockroach, the resulting footpath is designed to be the same. Three different sets of four bar mechanisms accomplish the same tasks performed by the cockroach's front, middle, and rear legs. These mechanisms are designed to operate such that the driven link may rotate continuously, permitting each leg to be driven by a single DC motor.

The kinematics of MechaRoach's legs was designed and simulated using WorkingModel 2D® software. MechaRoach was then simulated in WorkingModel 2D® to determine appropriate leg phasing and to assess stance and swing times. Climbing tests were also simulated using this software in order to ensure that the geometry of the robot would permit cockroach-like mobility.

2.1 Legs

A comparison of the cockroach and MechaRoach's sagittal plane footpaths is shown in Fig. 2. As illustrated, MechaRoach's front legs swing to head-height, while its middle legs move from a decelerating to accelerating position. The rear legs move linearly along the ground and push rearward.

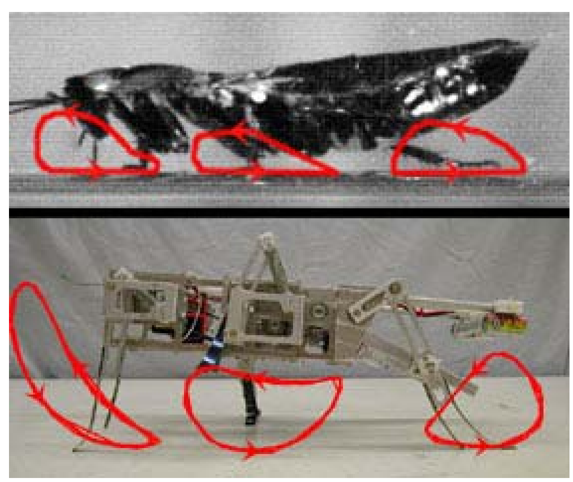

Fig. 2. Comparison of cockroach and MechaRoach footpaths. Scales are not equal.

The robot's front and middle legs are designed as "crank-rocker" closed-loop four bar linkages. The robot's leg is attached via revolute joints to a "crank" and "rocker" link. The driven link, or crank, is mounted to the drive train, transmitting torque to the robot's leg. The rocker link is mounted to the robot's body via a revolute joint, thereby constraining the leg's motion as a single-input, single output mechanism. The geometry of these individual links is tuned to recreate the cockroach's footpath in the sagittal plane.

Four of MechaRoach's legs also contain a compliant degree of freedom. The rocker links of the front and middle legs contain a spring-loaded prismatic joint. Under moderate-to-heavy loads, foot force is transmitted as a compressive load to the rocker springs. This causes the robot's leg to rotate upward several degrees, thereby lengthening stance and reducing impact loads.

MechaRoach's rear legs are designed as "crank-slider" mechanisms, which utilize both revolute and prismatic joints. This type of linkage was chosen to imitate the piston-like rearward motion that the cockroach exerts with its hind legs. A hollow Delrin slider translates on a square aluminum shaft and is connected to the leg by a revolute joint. This moves the robot's foot in a linear motion along the ground, in a manner reminiscent of the cockroach's rear foot motion.

MechaRoach's feet are modeled after the cockroach's tarsus, which passively flexes like a compliant foot. The tarsus is used to stabilize the animal's body during walking as well as cling to obstacles during climbing [5]. On a cockroach, the tarsi on the front and rear legs point frontward and backward, respectively, while the middle tarsi point away from the animal's sides. MechaRoach's tarsi are oriented in a similar fashion. They are each composed of two pieces of spring steel, formed to mimic the cockroach's tarsal shapes. The robot's feet provide compliance with the environment and springy resilience during walking and running.

2.2 Actuation

A single 90W Maxon motor with an integral 26:1 three-stage planetary gearhead drives MechaRoach. The motor drives an idler shaft, which in turn drives the front and middle axles via chains and sprockets, and the rear axle via a pair of 1:1 meshing spur gears. These spur gears are needed because the driving link for the rear legs run in the opposite direction as the other two sets of legs. The axles consist of solid hexagonal bars. MechaRoach is radio controlled and carries its batteries onboard.

The single motor design chosen for this robot permits any one leg with a foothold to receive all of the motor's available power. This saves considerable weight as compared to a multiple motor design in which each leg actuator must be selected based upon its own worst-case scenario. The use of only one motor, however, limits the possible behaviors of the robot. This drawback can be mitigated with the addition of some other simple abstracted cockroach mechanisms.

2.3 Body

MechaRoach's body design also draws from biological inspiration. The cockroach carries a considerable amount of its weight in its abdomen (Fig. 2), which places the cockroach's center of mass (CoM) near its rear leg-body attachment points when viewed from the sagittal plane. With its center of mass positioned far behind its head and front legs, the cockroach can easily rear itself up and onto an obstacle, which enables its powerful rear legs to drive it over the barrier. The location of the cockroach's CoM is important to its mobility.

MechaRoach's CoM is designed to be adjustable, allowing its location to be tweaked in order to obtain the efficient walking. For this purpose the location of the battery pack, which has significant mass, was designed to be movable. Thus, the CoM of the robot can be changed without adding extra weight. The battery pack is suspended from the rear of the robot on two cantilevered aluminum rails. This places a great deal of the robot's weight in its rear, in a manner that is similar to the large abdomen suspended over the cockroach's rear foot positions. The solution of locating the robot's power supply over its rear legs was directly inspired by the morphology of the cockroach.

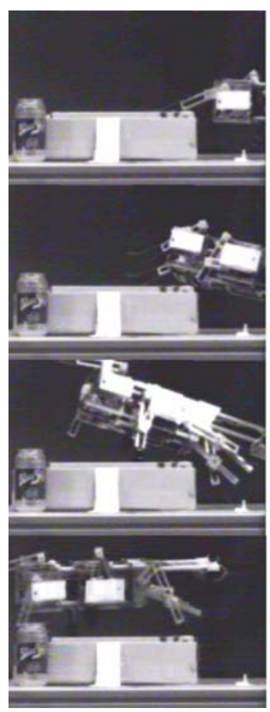

Fig. 3. MechaRoach climbing over a 4 inch obstacle

3.0 Experimental methods

The Ritzmann Lab at CWRU studies hexapod insect locomotion by analyzing high-speed video of walking cockroaches. In their setup, a treadmill maintains the insect's position relative to a set of high speed cameras. White tracking dots were placed on three sides of the head, thorax, and abdomen of the cockroach. Fig. 4 shows a schematic of the experimental setup [14]. The resulting three-dimensional data were digitized using WINanalyze® motion tracking software. Using this method, body motion data from a series of different cockroaches was taken.

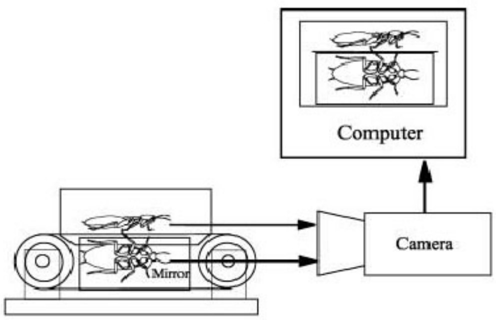

Fig. 4. Data collection for lateral and ventral views of the cockroach. Another camera, not shown, records the front view.

To study the locomotion of MechaRoach, a similar setup was devised. The robot walked on a large treadmill while a high-speed camera recorded video. However, due to space and equipment limitations, only a lateral view of the robot could be captured. Tracking dots were placed at the center of mass and head along the side of the robot facing the camera, and data was recorded using WINanalyze®. It was necessary to manipulate the raw video data because as the robot rolls about its horizontal axis, the tracking dots on the side of the frame no longer reflected the true CoM position. This was corrected by deducing the robot's roll angle from the locations of the near and far edges of its body frame. Taking the roll angle into account allowed for correction of the CoM position measurements so that they more closely reflect the true values.

4.0 Body motion in MechaRoach

MechaRoach can walk at one body length per second and climb over a step 4.75 in. high (70% of its body height and 75% of its maximum reach).

During walking, MechaRoach exhibits a regular, inverted pendulum-like gait. As it alternates between tripods, the robot's body rises and falls in a very predictable pattern. Fig. 5 shows results from a test of the robot walking at approximately 14 in/sec. The pitch angle and CoM position of the body oscillate at the same frequency, 2.5Hz, while the body roll oscillates at roughly half that value. All three measurements maintain the same phase relationships throughout the entire walk.

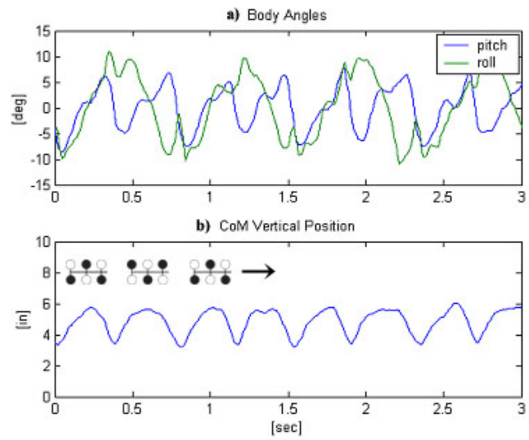

Fig. 5. High-speed video tracking of MechaRoach. (a) shows body attitude vs. time and (b) shows vertical position of the CoM vs. time. The colored dots indicate a tripod stance phase.

Each "hump" in the CoM position plot (Fig. 5b) corresponds to one complete stance phase. The minima on this graph occur during transitions between tripods. The center of mass experiences roughly a 50% height change during a given stance phase.

Within a single stride, MechaRoach's body undergoes two pitching movements and one roll movement (Fig. 5a). As a tripod stance begins, the robot is pitched down and rolling toward the side with two legs in contact with the ground. When these two legs begin to support load, the pitch and roll rotations are slowed and reversed. As the step continues and the CoM reaches its maximum height, the pitch and roll angles decrease to zero, and the robot briefly takes on a neutral posture. Near the end of the stride, the robot pitches up and begins to roll toward the opposite side of its body, where only one leg is in contact with the ground. Finally, as stance ends and the tripods begin to transition, the robot's body pitches down and continues to roll toward the side of its body where two swing-phase legs have now begun to initiate the next stance. From here, the process repeats. In a given stance phase, the robot's body pitches from down, to up, and back to down, and its body rolls from the side with two grounded legs toward the side with one.

5.0 Body motion in the cockroach

To better understand the body motion of the cockroach, data were collected from several cockroaches walking at between one to two body lengths per second. No escape responses were initiated in these cockroaches, and they were permitted to walk freely on the moving treadmill.

The data show that there is a significant degree of variability in cockroach body motion. Over a single test, a cockroach's roll, pitch, and CoM position can exhibit quite different patterns and magnitudes. Despite these variations, some trends were noted across the set of the animals tested. The cockroach's body attitude and CoM position all oscillate in phase with its tripod gait, albeit at varying frequencies. A significant overlap period exists between tripod stance phases in which all six of the cockroach's legs make contact with the ground. This overlap period can at times last as long as a tripod stance phase, and appears most prevalent at slower speeds.

Among all of the cockroaches' body motion data, rolling behavior appears most consistent. In almost every cockroach that is observed, the body tends to make one rolling motion per step. The cockroach begins stance rolled toward the side of its body with two legs in contact with the ground (its front and rear legs). As stance continues, the animal's body rolls toward neutral attitude and proceeds to roll toward the side of its body with one leg in ground contact (middle leg). This rolling motion is arrested when the tripod in swing enters stance and the tripod overlap period occurs. As the cockroach initiates its next tripod stance, its body is rolled once again toward the side of its body with two legs in ground contact, and the whole process simply repeats. Fig. 6 illustrates this rolling behavior. The cockroaches typically exhibit maximum roll angles of ±7 degrees.

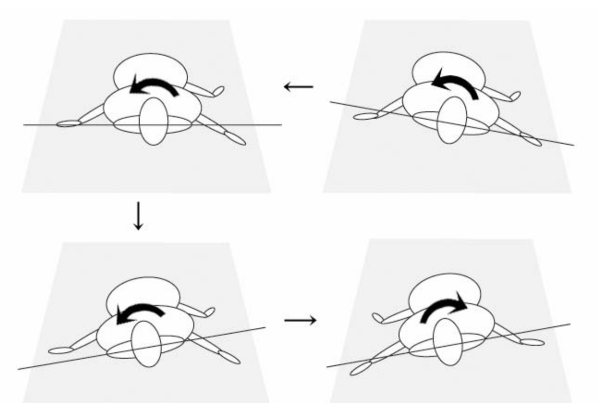

Fig. 6. Rolling motion in walking cockroaches. For clarity, only the tripod legs in stance are shown. Overlap periods are also omitted.

The pitching motion observed in the cockroach's body motion also indicates a trend, but it is less consistent than the rolling behavior. During slow walking, the cockroach tends to perform two pitching movements per step, one upward and one downward. At the beginning of a typical tripod stance, the cockroach pitches its body upward, as its leg drive its body forward. As the step proceeds, this upward pitching motion slows and is eventually reversed as stance nears an end. The cockroach's body then tends to pitch downward until the next tripod enters stance. During the tripod overlap period, the downward pitching is reversed and the cockroach's body pitch is once again driven upward. This completes the cycle and the process repeats over each successive step.

These pitching movements appear in many, but not all of the cockroaches that were tested. The magnitudes of these body pitch angles, however, appear much more variable. Some cockroaches tend to walk with an average positive body pitch angle (nose up), while others tend to walk pitched negatively. The cockroaches typically exhibit pitch angles over a range of about ±5 degrees. Overall, the pitching motions of the cockroaches are fairly consistent, but the angle magnitudes at which these motions occur are more unpredictable.

The motion of the cockroaches' centers of mass is the most variable parameter measured in these studies. The cockroach's center of mass tends to oscillate approximately ±10% of its nominal height, and generally moves in response to the animal's gait pattern. However, the frequency of its oscillation fluctuates from test to test and from animal to animal. At times an animal's center of mass position may vary at the same frequency as its stepping pattern, and at other times it may vary at half that frequency. Few overall trends emerge in this particular parameter, and it seems that a larger study must be done to fully characterize it.

6.0 Comparison of body motion in MechaRoach and the cockroach

MechaRoach exhibits rolling and pitching behaviors that are very similar to the cockroach.

Both MechaRoach and the cockroach roll their bodies once per step, rolling away from the sides of their bodies with two grounded legs toward the sides with one. This motion appears in repeated tests of the robot and the animals. The key difference that appears between MechaRoach and the cockroach in terms of rolling motion lies in the magnitudes of the angles, in which MechaRoach's are consistently larger. Otherwise, the robot and the animal roll their bodies in a very similar pattern during slow walking.

MechaRoach's pitching motion is also similar to the cockroaches'. While body pitching in the cockroach is a variable measurement, the typical pattern of an "up-down" pitch motion appears quite similar to MechaRoach. MechaRoach tends to pitch its body upward and downward during a single step, and several cockroaches exhibited the same sort of behavior. However, MechaRoach pitches its body much more severely than the cockroach, and always oscillates about a neutral attitude. Cockroaches, on the other hand, may oscillate about positive, neutral, or negative average attitudes, and the magnitude of these oscillations tends to be quite variable. Therefore, MechaRoach demonstrates cockroach-like pitching *motions*, but not necessarily cockroach-like pitching *magnitudes*.

The roll and pitch motions observed in these cockroaches also agree with qualitative observations given by Kram et al. [7] and Ting et al. [13].

MechaRoach's center of mass movement is highly regular and moves like a rigid pendulum, while the cockroach's center of mass may move in a variety of ways. The only apparent similarity between the CoM motions of the robot and animal is that they both move in response to stepping patterns. Therefore, the motion of the cockroach's CoM is most likely rooted in its gait, but the dynamics that link the two may be different than in MechaRoach.

7.0 Conclusions

MechaRoach's cockroach-like footpaths enable it to walk and climb in a cockroach-like manner. MechaRoach is the first generation of a new series of robots being developed in the CWRU Biorobotics Lab that employ abstracted biological principles to recreate cockroach stepping patterns and footpaths using simple mechanisms. MechaRoach incorporates key characteristics of the cockroach's design, and the result is a robot that can walk rapidly and climb obstacles that are large relative to its own size.

MechaRoach's abstracted biological design also causes it to exhibit cockroach-like body motion as it walks. Experiments conducted in our lab indicate that the bodies of walking cockroaches exhibit relatively predictable roll and pitch motions. The body of MechaRoach moves quite similarly to these cockroaches during slow walking. This indicates that the ground level limb movements like footpaths and the tripod gait result in predictable patterns in body motion. These experiments suggest that stepping pattern and foot trajectory play a significant role in body motion, and that regardless of whether a vehicle is fairly rigid like a robot or compliant like an animal, similar foot motion can result in the similar body motion.

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