Insect-like Antennal Sensing for Climbing and Tunneling Behavior in a Biologically-inspired Mobile Robot[*]

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***Abstract* - Through the use of mechanical, actuated antennae a biologically-inspired robot is capable of autonomous decision-making and navigation when faced with an obstacle that can be climbed over or tunneled under. Vertically-sweeping mechanical antennae and interface microcontrollers have been added to the Whegs™ II [1] sensor platform that allow it to autonomously sense the presence of, and successfully navigate a horizontal shelf placed in its path. The obstacle is sensed when the antennae make contact with it, and navigation is made possible through articulation of the Whegs™ II body flexion joint.**

***Index Terms* – Whegs™, Biologically-inspired, autonomous navigation, mobile robotics, cockroach.**

I INTRODUCTION

When faced with an option to climb over or under an object, a cockroach (*Blaberus discoidalis*) uses contacts of its antennae with the obstacle as aids in determining the course of action. The cockroach will almost always follow the route discovered by both antennae if they agree. For example, if both antennae touch an upper surface, the cockroach will climb; if both sense an opportunity to tunnel, the insect will do that instead. There is a decision to be made, however, if the antennae do not agree. Mechanical implementation of this behavior is desired to provide a level of autonomy to climbing-capable mobile robots.

While there are several robotic platforms available to use as a base for implementing antennal sensing, the Case Western Reserve University's Biorobotics Laboratory Whegs™ II robot (Fig. 1) is an ideal choice. Its energetic and simply-controlled Whegs™ locomotion allows for ease of implementation for speed-related calculations while maintaining a high level of climbing ability. The climbing capability is raised over other similar robotic platforms such as Whegs™ I and RHex [5] by the inclusion of a body flexion joint that allows Whegs™ II to climb obstacles over twice its leg length and avoid high-centering situations.

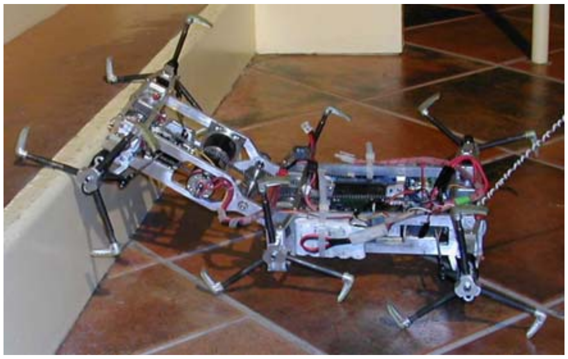

Figure 1. Whegs™ II uses three spoke simplified legs that can reach the top of a barrier that is higher than the length of a spoke. Body flexion is used to rear the front half of its body.

II WHEGS™ II FEATURES

Whegs™ II uses a single 90W Maxon DC motor to propel all six of its legs. The drive motor is coupled with an integral 26:1 three-stage planetary transmission, which produces more torque with less frictional losses.
The single propulsion motor design reduces the robot's weight and improves its power to weight ratio [1][4].

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™ vehicle's three-spoke appendages, called Whegs™ (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.

The simplified legs are installed on the vehicles such that they form a tripod gait [6]. Whegs™ II uses 10cm long spokes that move in the sagittal plane (Fig. 1). Each leg is constructed of rubber-coated spring steel, which offers abundant traction and radial compliance.

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Whegs™ II is steered by two small R/C servos that are electrically coupled to rotate the front and rear legs in opposite directions. Cockroaches turn in a similar manner; however all three pairs of their legs are engaged in turning their bodies [2]. The body and geometry of Whegs™ II gives it a turning radius of 1.25 body lengths. The tripod gait is not always suitable for a hexapod. In fact, when climbing larger barriers, cockroaches often move their leg pairs in phase [12]. The axles of Whegs™ II incorporate compliant mechanisms, which accomplish phase changing passively [1][4].

Whegs™ II has compliant mechanisms in all six of its axles. These mechanisms cause them to run in a nominal tripod gait [6], but passively adapt their gaits to irregular terrain (Fig. 1). 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. [3].

A cockroach enhances its climbing abilities by changing its body posture before and during a climb over an obstacle [12]. For example, it performs a rearing movement prior to climbing obstacles that are taller than it could normally reach with its front legs (Fig. 2). A Whegs™ vehicle cannot rear up using its middle legs. However, it can accomplish the goal of raising the front legs higher by rotating a body joint upward. Cockroaches have a thoracic body flexion joint located between their front and middle thoracic segments that enables them to bend the front half of their bodies downward. 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.

Whegs™ II has a body flexion joint that is collocated with its middle axle and is actuated by an R/C servo. The front of its body can be flexed up (Fig. 1) or down 30 degrees from the neutral position. In Fig. 1 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. Using its body flexion joint Whegs™ II can climb obstacles that are higher than twice its leg length

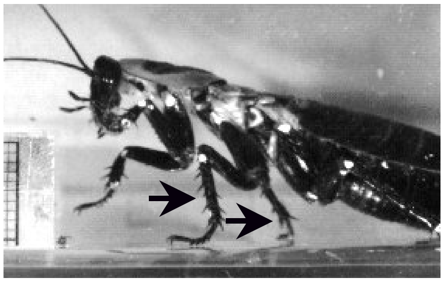


Figure 2. Cockroach rears it body prior to climbing.

III ANIMAL ANTENNAL USE

Antennae are responsible for much of the orientation behavior exhibited by cockroaches. This tactile orientation behavior can be used for wall following [7], identification of a predator [8], and object guided orientation [9]. Antennae may also be used for navigation in complex environments.

Cockroach antennae consist of many segments. The most proximal segments are the scape and pedicel which are covered by hairplates that encode mechanosensory information about object position [9]. When the flagellum of the antenna touches an obstacle, hairs on these plates are deflected. This deflection results in sensory signals which encode information about the position of the obstacle [10]. Despite the large range of motion of the antennae (~360˚) they only use a small portion. Sensory hairs on the dorsal scapal hairplate of the antennae (thought to be involved in obstacle detection) are almost all deflected at 60˚ above the body axis [10], and the angle below the body axis is limited by the ground, unless the animal is on a ledge. Therefore, it is possible that the animal would benefit most from focusing on the area in which it has finely tuned sensors.

Walking animals perform wide searching movements with their antennae. During walking behavior in stick insects it was noticed that the antennal oscillations seem to be coupled to walking speed [11]. The protraction phases of the antennae are coupled with the stance phase of the corresponding limb; however, this coupling is not exact. The antenna reaches the posterior extreme 0.2-0.25 cycles prior to the corresponding leg [11]. These antennal movements, which occur out of phase, give the animal more information about its environment than it would get from stationary antennae or if the antennae were in phase.

Antennal contact is critical to many transitional behaviors. When an insect encounters an obstacle, the antennae touch first. The animal will then often make repeated antennal contacts while continuing to approach the obstacle. Once close to the obstacle, the animal can change body attitude such that it will be able to make a climbing trajectory [12] (Fig. 2). In walking stick insects, gap crossing behavior only occurs if the animal first detects the gap with the antennae. Otherwise, no change in behavior is observed. If the animal then places a foot in the gap, it pulls back and searches the area with its antennae until the substrate across the gap is discovered [13]. Once this occurs, the insect proceeds with forward movement. Preliminary data from two of our authors indicate that when presented with a shelf, cockroaches can distinguish between the top of the shelf and the bottom and then respond with the corresponding climbing or tunneling behavior.

IV MECHANICAL ANTENNAE IMPLEMENTATION

A mechanical set of antennae were designed to attach to the Whegs™ II robot. The antennae are two 457mm long, 3mm dia. fiberglass rods attached to the output horns of MPI 350HP R/C servo motors and covered with Interlink Model 408 force-sensing strips on the top and bottom. The servo motors are attached to hinged brackets that allowed the antennae to rotate backward. In the event the robot elected to tunnel under the shelf while one antenna was still above it, this feature allows the antenna and servo assembly to rotate backward rather than become damaged or impede the robot's progress. The hinged sections are held in place by magnets to prevent this backward rotation movement during normal operation.

Antennal contact is determined by measuring signal deviation in a voltage divider network using force-variable resistive sensors. The force sensors are connected to a 4.8vdc microcontroller-based A/D converter via 10kΩ pull-up resistors.

V SYSTEM MODEL

The goal of the system is to have a pair of head-mounted antennae detect a horizontal shelf, placed across the path of the robot, which offers the option of climbing over it or tunneling under it. A state-based system model was developed to capture the desired behavior of the robot and antennae. Initially, the robot begins and remains in a Seek state. In this state the robot moves forward and the antennae oscillate at different rates and change direction when an upper or lower position is attained. The oscillation rates are maintained at constant speeds with varying direction, and do not have sinusoidal velocity.

When an antenna registers contact with the target, forward motion of the robot is stopped, the antenna making contact stops oscillating (while the other antenna continues), and a timer is started. This gives the second antenna time to make contact by preventing the robot from driving past a point where contact can occur. The timer is used so that the robot doesn't wait indefinitely for two antennae to detect an obstacle. Situations could arise due to mechanical damage or failure (i.e. a missing or immobile antenna), or when only one antenna is able to sense the obstacle due to orientation with the target.

As the second antenna contacts the shelf, or the timer expires, a decision to climb or tunnel is made. The decision is always made in favor of a path determined by two antennae on the same side of the shelf. So that both antennae sensing the top of the shelf will cause a climbing behavior (scenario 1) and both antennae contacting the underside of the shelf will cause the robot to tunnel (scenario 2). If one antenna senses the target and the timer expires before the other antenna makes contact, the robot will move toward the side that the first antenna contacted (scenario 4). The other scenario (scenario 3) occurs when one antenna contacts the top of the shelf and the other antenna contacts the underside. In this situation, the robot will perform a tunneling behavior. A tunneling behavior was chosen for this scenario as it seems to be the "safer" route the robot could take: less exposure, less likely to fall.

TABLE I
TWO-ANTENNAE SIMULATION PARAMETERS

Parameter\Trial	**1**	**2**	**3**	**4**	**5**
R Antenna Rate (deg/sec)	2.0	4.0	6.0	8.0	10.0
L Antenna Rate (% of R)	80	85	90	95	100
Antennae y_{min} (in)	1.0	1.5	2.0	2.5	3.0
Antennae y_{max} (in)	5.0	5.5	6.0	6.5	7.0
Robot Speed (in/sec)	3.0	6.0	9.0	12.0	15.0
Target Distance (in)	24	30	36	42	48
Contact Timeout (in)	2.0	4.0	6.0	8.0	10.0

VI SIMULATION

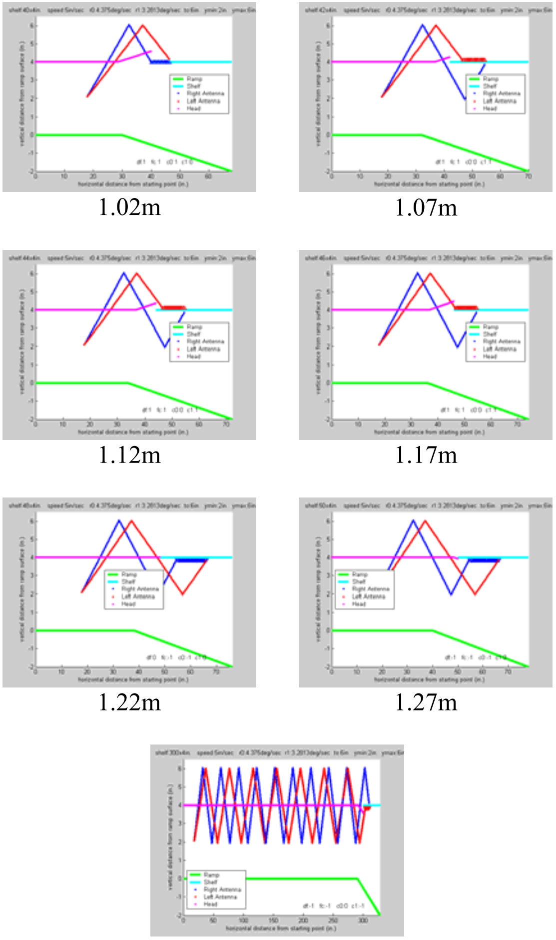
The system model was simulated in Matlab with a variety of system and environment parameters, and was used to examine the relationship between the various parameters. The following parameters were varied to test for inter-dependence: Antennae Oscillation Rates, Antennae Sweep Ranges, Robot Speed, Initial Distance to Target, and Second Antenna Contact Timeout Value. Each parameter had five values selected for simulation while the other parameters were fixed at the middle values for each test. Table I shows the selected values.

The Contact Timeout parameter represents a distance, and consequently a time, after the first antenna contacts the obstacle within which the second antenna must also contact the target. If the second antenna does not contact the target within that distance (time period), a single-antenna contact decision is made. For all simulations, Antennae Length was 457mm., Head and Ramp Heights were equal at 102mm, and the Time Interval between samples was 0.05sec.

In order to maintain a balance between high resolution sensing and low power consumption, an acceptable robot speed-to-antennae oscillation rate needed to be implemented. In an ideal case this value should be infinitely small, indicating an extremely high antennae oscillation rate. However, this was both impossible and impractical. Also, the second antenna should have a lower oscillation rate than the first to sense more area; since as the second antenna oscillation rate increases toward 100% of the first, the system appears to have only one antenna.

While the exact frequencies and phase differences in observed insects could not be quantified due to extreme variability, the dissimilar oscillation rates between the two antennae were implemented in the robot simulations. Through Matlab trials, a good balance between low oscillation rate and high coverage area was having the right antenna oscillate at 87.5% of robot speed and the left antenna oscillate at 75% of the right antenna rate. These values provided a nice compromise between motor exertion and coverage of the vertical plane (Fig. 3, 7.62m image), and were easily implemented using the BrainStem microcontroller. Fig. 3 shows the results for varying starting distances from the shelf. The dark blue line is the path of the right antenna; the red line is the path of the left antenna. Heavy blue and red symbols indicate that the corresponding antenna had made contact with the shelf and had stopped oscillating. The fuchsia line is the path of the robot "head". It remains at a height of 102mm until a decision to climb or tunnel is made, when it deflects up or down in the image. The shelf and approach ramp positions are shown in cyan and green, respectively.

One observation from the simulations is that antennal position becomes a function of distance when related to robot speed. As the physical distance is limited to a maximum of 1.32m in the test environment, a minimum oscillation rate was implemented, preventing the antennae from oscillating at a rate of zero. This changes the system to become a function of time rather than distance. By waiting different times before initiating forward motion toward the obstacle, different antennal contact scenarios can be encountered.



1.02m 1.07m

1.12m 1.17m

1.22m 1.27m

7.62m

Figure 3.
Right Oscillation Rate (blue line) = 0.875*(Robot Speed)
Left Oscillation Rate (red line) = 0.75*(Right Oscillation Rate)
Robot Head (fuchsia line), Shelf (cyan line)
Approach Path and Ramp (green line)
Note: Vertical and horizontal axes represent height and distance, respectively. Numeric caption denotes starting distance from the shelf

VII TEST ENVIRONMENT

The physical environment for the Whegs™ II robot antennae experiments (Fig. 5) is a 0.61m wide, 1.83m long raised approach path with a 95cm ramp descending at 15.5°. In addition, a 1.22m wide, 0.61m long shelf that straddles the ramp provides a climbing option as well as a tunneling option for travel. The shelf has adjustable height, but was set to correspond with the height of the robot's "head".

VIII SOFTWARE BEHAVIOR IMPLEMENTATION

The Whegs™ II robot is radio-controlled with a three-DOF wireless FM transmitter (72 MHz, Channel 50). The transmitter allows an operator to control speed (forward and reverse), steering (left and right), and flexion of the body joint (up and down). For these experiments, R/C commands were intercepted en route to their respective motors and interpreted by an Acroname BrainStem GP 1.0 microcontroller, which recreated the speed and steering signals, but impeded the body joint flexion signal from the user. A second BrainStem GP 1.0 module was used to actuate the antennae motors and sense antennal contact via an onboard A/D converter. The two microcontrollers were connected to one another via an I^2C communications bus.

The implemented behavior began by reading the robot drive speed signal from the R/C receiver. This signal was used to determine antennae oscillation rates with the boundary of 8-23% of the maximum possible robot drive speed. While in the bounded region, actual drive speed was used for antennae oscillation rate calculations; outside the region, the floor or ceiling value was used. Each antenna continued oscillating until object contact was sensed, at which time the robot drive motor signal was impeded to stop further forward movement. A timeout period of 1 / (% robot speed) msec. was initiated when contact was sensed, providing a period inversely proportional to speed, during which the other antenna continued to oscillate. When the second antenna made contact with the shelf, or the timeout period expired, oscillation of the second antenna was stopped and a climb/tunnel decision was made. The robot speed signal was retransmitted and the body flexion joint was actuated in the direction of the decision for a time of τ = (% robot speed) * 128/100 sec. The body flexion joint was then straightened for τ sec., and then actuated in the opposite direction for τ sec. Finally, the body flexion joint was again straightened. This series of movements would allow the Whegs™ II robot to properly surmount or tunnel under a shelf.

The programmed behavior faithfully follows the system model described in Section 5.

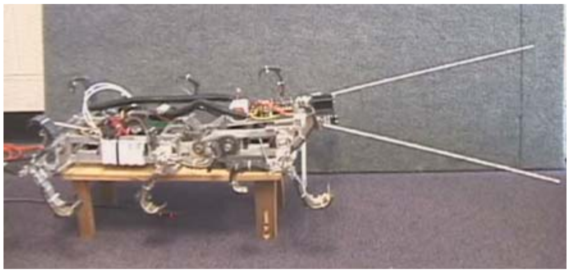


Figure 4. Whegs™ II with initial antennae design during stand-based testing

IX RESULTS

The original antennae design measured the difference in commanded and actual position to determine contact with the shelf. However, due to repeated sensing of false positive readings because of antennal inertia while the robot was running, initial testing was performed with the robot on a stand. The stand allowed leg movement and body flexion while remaining stationary (Fig. 4). A series of tests were performed by manually bending the antennae to simulate contacting an obstacle. This was performed to test each of the four scenarios: both antennae on top; both antennae underneath; antennae split by the shelf; and single antenna contact. Split antennae and single antenna contact scenarios were performed for each permutation of left and right antennae contact configurations. The testing was video taped and showed that the program modules were performing as expected, and the climb/tunnel decision was correctly being made and executed. Each scenario followed the sequence of programmed states and actuated the body flexion joint correctly to achieve the desired climb/tunnel response.

A second, more robust, design used flex sensors to measure antennal deflection to determine shelf contact. However, it was also unable to tolerate the severe antennal flexion while walking on the ramp and was tested on the stand.

Finally, with the third antenna design, Whegs™ II was able to navigate the test ramp without causing false-positive readings (Fig. 5). This allowed full testing of the behavior and was video taped. With the unpredictability of how the antennae would contact the shelf, it was difficult to capture each of the four scenarios.

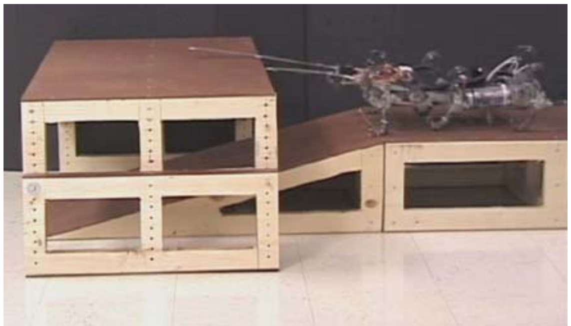


Figure 5. Whegs™ II on the test ramp with antennae contacting the shelf on the top and bottom (scenario 3)

TABLE II
WHEGS™ II RAMP TRIAL RESULTS

Result	**# Times**
Scenario 1	1
Scenario 2	1
Scenario 3	5
Scenario 4	2
False Positive Contact	2
Missed Shelf	1

In several of the trials, an antenna speared the front face of the shelf causing extensive flexing (Fig. 6). The flexing registered as a pressure contact on the sensor outside the curve. In each case where this occurred, the antenna flexed upward, stressing the upper sensor and registering as making contact with the underside of the shelf.

Since the antennae are constantly moving, and at varying rates, there is a limited potential for both antennae to contact the same side of the object. This results in more cases of scenario 3, but increases the likelihood of contact the shelf at all (Fig. 3, 7.62m image).

During two of the trials, false positive contacts were observed. For these trials, the motion of Whegs™ II caused severe flexing of an antenna, which signaled a contact situation. The trials were stopped before viewing any resulting behavior action and the contact force thresholds for the antennae were increased after the second incident. In one trial, the robot drove under the shelf without making contact with it. After this trial, the range of antennae oscillations was increased to cover more area above the shelf.

For each trial that a contact scenario occurred, the robot successfully performed the body joint flexion behaviors and navigated the shelf.

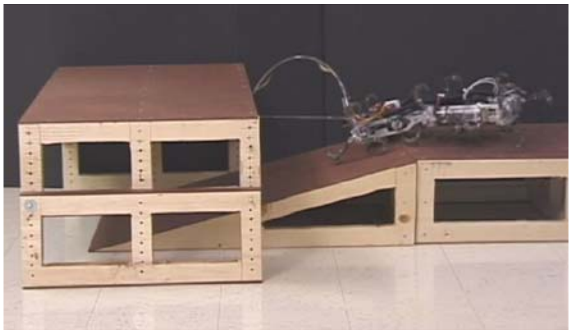


Figure 6. Scenario 4 event while testing on the ramp

X CONCLUSIONS

This research showed that the addition of biologically-inspired mechanical antennae enhanced the autonomy of the Whegs™ II robot in situations where climbing and tunneling options are provided. Future work will be performed to improve the robustness of the current system, and further enhance the level of autonomy. Additional automations, already in progress, will allow Whegs™ II to navigate the ramp without user assistance.

This includes speed and inertia control, and ramp edge detection for course-correcting steering.

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