

A Hexapod Walks Over Irregular Terrain Using a Controller Adapted from an Insect's Nervous System

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Abstract—Insects have long been a source of inspiration for the design and implementation of legged robots. Their extraordinary mobility, agility, and adaptability are features sought after when developing competent, useful mobile walkers. Externally witnessed behaviors have been successfully implemented in walking robots for decades with great success. More recent years of biological study have solved some of the mysteries surrounding the *actual* neurobiological methods for mobilizing these legged wonders. This paper describes the first implementation of these neurobiological mechanisms in a physical hexapod robot that is capable of generating adaptive stepping actions with the same underlying control method as an insect.

I. INTRODUCTION

WALKING robot designers have often turned to nature for inspiration. Insects are remarkable animals that are agile, adaptive, and integrate multi-modal sensory systems to navigate their environments. These are all traits that are desirable in legged robots.

Early hexapod designs, such as Genghis [4] focused on incorporating sensory systems with walking systems so that interactions with the environment altered walking behaviors. This was accomplished by building and combining layers of augmented finite state machines that, when interconnected, form an expansive series of behavior patterns.

Later robots such as Robot I [3], Robot II [9], and the Tarry series [10] focused on implementing observed insect behaviors into walking robots. Leg movements and gait generation emulated those of actual insects in order to create biologically-inspired hexapods that could move similar to their animal counterparts. Gait generation was based upon rules discovered by Holk Cruse [5], [6] after years of studying stick insect walking behaviors.

While these examples produced adaptive, legged, biologically-inspired hexapod robots, the implementation of *insect behaviors was based on external observation, and not neurobiology*. The behavioral outcome was similar, but the method of creating the outcome was not duplicated. Instead it relied upon engineering solutions to achieve walking;

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some methods required advanced mathematics and intense computations.

As identified by Hess and Büschges [11] and Ekeberg *et al.* [8], stick insect neurobiology uses a series of sensory-coupled oscillators in the thoracic ganglia, with an oscillator for each joint that controls leg movements. These locally-driven joints are influenced by sensory signals associated with the joint itself, other joints in the leg, and from descending commands from the brain to create stepping patterns. These patterns are altered by interaction with the environment to create responsive, adaptive stepping that allows the insect to conform to its surroundings.

Such neurobiologically-based leg control has been done previously in simulation [8] and with single- and two-legged platforms [13]. This work represents the first implementation of this method in a physical, and completely autonomous, hexapod robot that is capable of adaptively navigating its environment (Fig. 1).

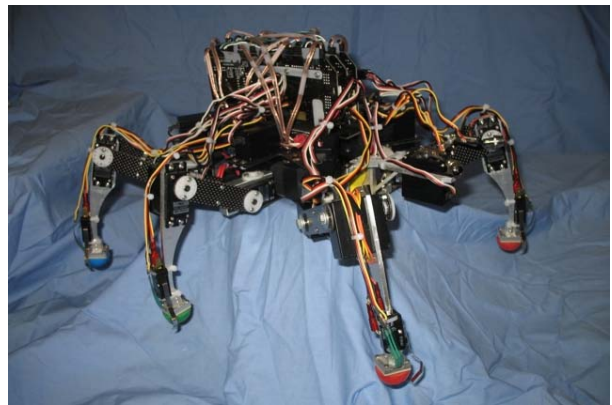


Fig. 1. BILL-Ant-a (Biologically-Inspired Legged Locomotion-Ant-autonomous) walks autonomously and adaptively on irregular terrain using a neurobiologically-based leg control method identified in insects.

II. BILL-ANT-A

A. Robot Design

BILL-Ant-a (Biologically-Inspired Legged Locomotion-Ant-autonomous) is an autonomous hexapod constructed from aluminum and carbon fiber. Its six legs each have three active degrees-of-freedom (DoF) and two passive DoF, and a 1-DoF articulated neck carries two optical sensors. The central chassis, legs, and batteries are the same as BILL-Ant-p, a prototype walking hexapod with tethered, off-board control employing inverse kinematics for joint

movements, and a subset of Cruse’s rules for leg coordination for gait generation [12].

Active DoF in the legs and neck are actuated by MPI-MX450HP hobby servo motors (Maxx Products, Inc., Lake Zurich, IL, USA). The motors are capable of delivering up to 116oz-in (0.82N-m) of torque and directly drive the joints of the legs and the neck with a ± 45 degree range of motion. This torque is sufficient to allow the 5.1lb (2.32kg) robot to walk with a payload of up to 7.0lbs (3.18kg).

The motors power three joints in each leg in a configuration based on a subset of insect leg joints. The most proximal joint is the thorax-coxa (ThC) joint responsible for protraction and retraction of the leg. The next is the coxa-trochanter (CTr) joint that levates and depresses the leg. Finally, the femur-tibia (FTi) joint allows the tibia to extend and flex relative to the femur (Fig. 2).

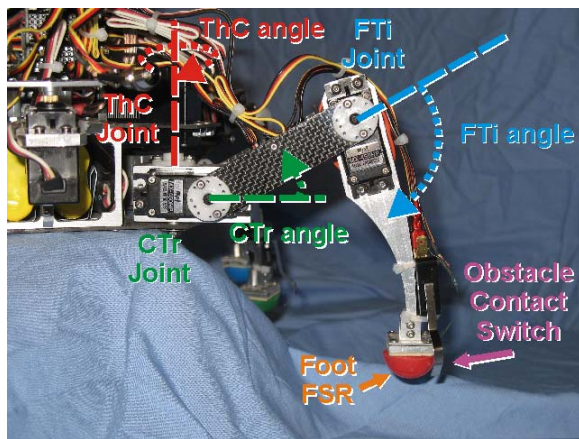


Fig. 2. BILL-Ant-a front-left leg with joints and sensors labeled.

Within each leg are two passive degrees-of-freedom. The first is a force-sensitive resistor (FSR) mounted in the foot that is used to identify ground contact. A switch mounted on the front of the lower tibia indicates when contact is made with obstacles in front of the leg.

Each leg is controlled by a low-end PIC-based microcontroller (BrainStem GP 1.0 by Acroname, Inc., Boulder, CO, USA). These microcontrollers implement the role of the thoracic ganglia and are responsible for: motor control of the three joints in the leg; reading sensory information from the two passive DoF; and sharing leg influence data during its stepping cycle with its adjacent neighboring legs, in order to create coordinated walking gaits. These microcontrollers were chosen specifically for their limited computing ability in order to illustrate the mathematical simplicity of the neurobiologically-based control method, and for the number of motor and sensor ports (four PWM servo controller, five digital I/O, and five analog ADC ports). The distributed controller network communicates via IIC bus.

A seventh BrainStem microcontroller serves two functions. The primary role is to act as the brain and subesophageal ganglion where it processes sensory

information from two phototransistors mounted on the neck. It actuates the neck in order to maintain balanced light levels (the visual stimulus and light-based goal for the robot) between the two sensors. The neck position is then used to modulate setpoint values in each of the leg controllers, which causes the robot to walk toward the light-based goal.

B. Intra-Leg Joint Coordination to Generate Stepping

As was reported in the work by [11] and [8] stick insects are strongly dependent on sensory information to generate stepping motions. Actions of individual joints within a single leg are influenced both by sensory systems associated with the joints themselves (intra-joint influences) and those systems associated with other joints within the same leg (inter-joint influences). The combination of sensory data such as joint angle and joint load is used to determine the joint’s direction of movement (Fig. 3).

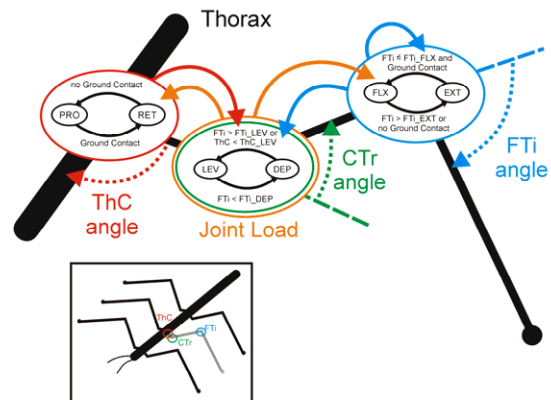


Fig. 3. Sensory-coupled joint controllers for a 3-DoF of a stick insect middle leg. Arrows indicate sensory influences; arrows from a joint to itself are intra-joint influences and arrows from one joint to another are inter-joint influences.

A stepping cycle includes a series of four stages: swing, pre-stance, stance, and pre-swing (Fig. 4). Transitions between the stages are initiated by sensory information generated through interaction of the leg with the environment and the physical connectivity of the joints to one another via the leg segments. Each stage is unique due to the combination of the motions of each of the three joints.

Swing is identified by protraction of the thorax-coxa (ThC), levation of the coxa-trochanter (CTr), and extension of the femur-tibia (FTi). This combination serves to lift and move the leg forward and is initiated by sensing a decrease in the load associated with the CTr joint. Pre-stance lowers the foot while still in the air in preparation for the onset of stance. This stage has joint movements of: ThC – protraction; CTr – depression; and FTi – extension, and begins when the FTi joint is extended beyond the transition threshold.

During the stance stage, the leg is both supporting and propelling the body. Initiated when sensing an increased load at the CTr joint (a sign of achieving contact with the ground), the joint directions change such that the ThC now retracts, the CTr continues depressing, and the FTi flexes.

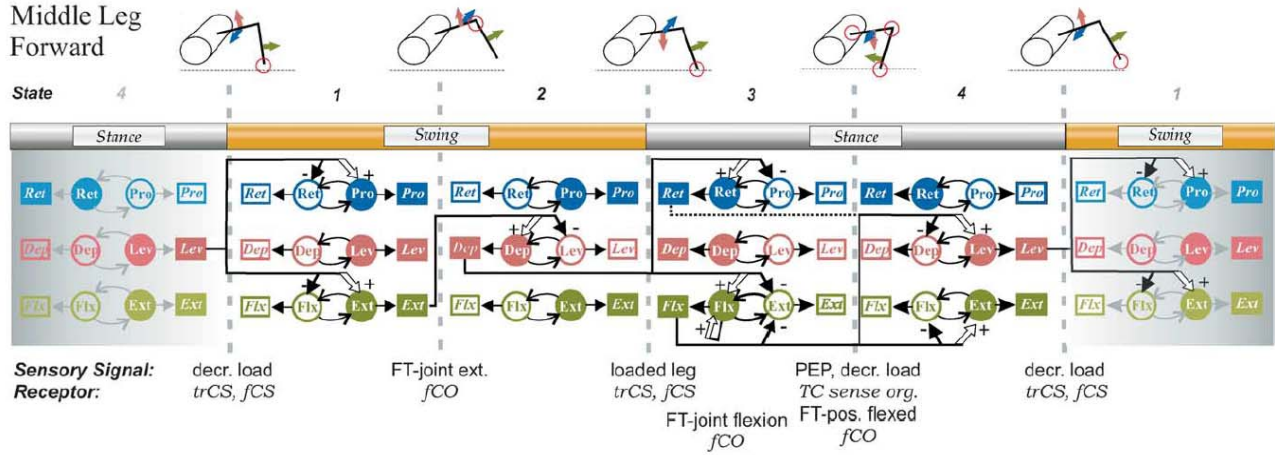


Fig. 4. Stages of a stepping cycle for a leg during a single step. Joint direction changes are influenced by sensory cues generated by the leg's interaction with the environment and the physical connectivity of the joints via the leg segments. Figure taken from [7].

Finally, pre-swing begins to unload the leg in preparation for the swing stage and starts when the FTi has flexed to its threshold position. While the ThC still retracts, the CTr now levates to begin unloading the leg, and the FTi extends. Once the CTr is unloaded, the cycle repeats with the swing stage.

Since joint movements are influenced by interactions with the environment, stepping actions are reactive, adaptive, and emergent. This allows the robot to conform to, and navigate over, irregular terrain.

The joint coordination method implemented on BILL-Ant-a is described further in [14].

C. Inter-Leg Coordination for Gait Generation

Behavioral observations of stick insects done by Cruse [5], [6] led to the development of a set of rules that defined mechanisms that determine stance/swing and swing/stance transitions. The implementation of these rules created speed-dependent continua of gaits in hexapod robots [9], [10], [12]. Gait generation in BILL-Ant-a is accomplished with a similar, but less computationally-intensive, method based on a subset of these rules, sufficient to enable walking [13].

Leg influence values are generated for each leg based on the joint angle of the thorax-coxa (ThC) joint, which represents the distance along the foot path that the leg has moved. The joint angle is divided by the nominal step length to create a percentage of the foot path that has been completed. A special value of 900 is chosen if the leg is currently in swing (Fig. 5).

Influence values are shared with orthogonally adjacent legs (i.e. the middle-left leg influences and is influenced by the front-left, middle-right, and rear-left legs, while the front-right leg is influenced by the front-left and middle-right legs). The average of the neighbor influences is subtracted from the influence the leg currently is being

assessed (Eq. 1). If the result is negative (caused by the large value of a neighbor leg in swing), the leg remains on the ground and continues to retract and support the body. When the result is positive, but within a pre-set threshold, the leg steps early. This threshold represents that a neighboring leg is close to completion of its stance phase, but that the leg in question can still complete a swing phase in time. Early stepping reduces or eliminates the amount of time that a neighboring leg will need to remain in stance while waiting for the leg to complete its swing phase.

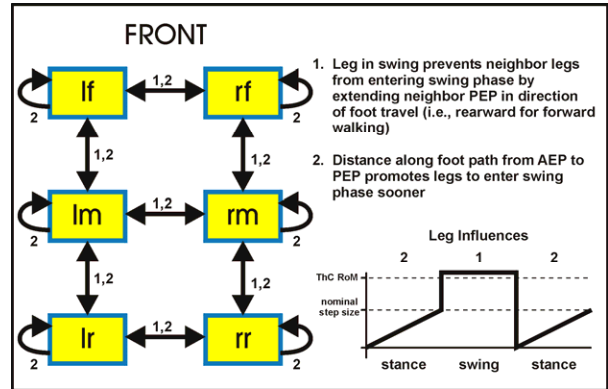


Fig. 5. Leg influences that generate coordinated, speed-dependent gaits. The two mechanisms involved represent the angle of the ThC joint, which is used to determine the amount of a single step that has been completed; and a large value for when the leg is in swing phase, which is used to inhibit the initiation of the swing phase in neighboring legs.

$$\begin{aligned} \text{stance influence} &= \text{ThC angle} / \text{foot path length} \\ \text{swing influence} &= 900 \end{aligned} \quad (1)$$

$$\text{net influence} = \text{leg influence} - \sum \frac{\text{neighbor influences}}{\text{number of neighbors}}$$

Since the leg influence used when a leg is in swing is larger than three times the maximum possible value that can be generated by a leg in stance, the resulting calculation is

decidedly negative, which prevents the possibility of any two neighboring legs being in swing simultaneously. This ensures the static stability of the robot.

III. HYPOTHESIZED SENSORY PATHWAY ADDITIONS FOR CREATING REFLEXES

As previously described, the robot is capable of stable, straight walking on level surfaces. While this is sufficient to demonstrate the success of the controller, it has limited application for a walking robot. Such level surfaces are more conducive to wheeled vehicles instead. But, on uneven terrain, legged robots have the ability to adapt and navigate the irregular surface

To help accomplish this feat, two hypothesized, biologically-plausible, sensory pathways have been suggested for addition to the sensory-coupled leg control model (Fig. 6). These pathways are based on biologically-verified sensory inputs and are used to inform the leg controller that an obstruction requiring a behavior other than normal, straight walking has been encountered. Upon sensing an obstacle, changes in the leg/environment interaction result in a cascade of reflexes [16] that alter the normal behaviors of the joints.

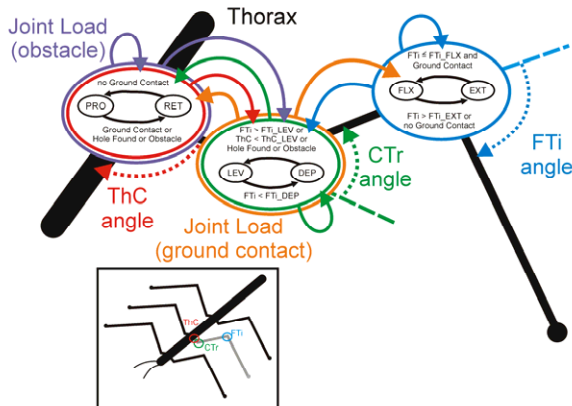


Fig. 6. The addition of two biologically plausible hypothesized sensory pathways representing the load of the ThC joint and the joint angle of the CTr can be used to initiate reflex behaviors necessary to navigate past obstructions.

A. Elevator Reflex

The elevator reflex prompts the robot to step over surmountable obstacles that are higher than the nominal step height [1], [2]. Increased load value information from the ThC joint indicates that an obstruction has been encountered while the leg is protracting during the swing phase. Alternately, as has been implemented in BILL-Ant-a for simplicity and the elimination for the need to perform additional sensory filtering of an analog load signal, a contact sensor near the foot can be used. This switch is depressed when the foot touches an obstacle.

When the sensory signal representing contact with an obstruction is identified, the elevator reflex is initiated (Fig.

7, bottom). This reflex changes the normal swing and pre-stance joint motions to become: retraction, levation, and extension. The retraction reduces the risk of snagging on the obstacle, while the levation action is conducted with a higher level of muscle activation in order to more-rapidly raise the leg and surmount the obstacle. Also, the updated joint directions are only momentarily changed, then allowed to return to their normal directions based on sensory cues. That is, once contact with the obstacle is ended, the leg will resume protraction, depression, and extension. If contact is again made with the obstacle before it is surmounted, the reflex is initiated another time.

B. Searching Reflex

The searching reflex is employed to step beyond gaps or holes [1], [2]. The leg has memory for where it last contacted the ground by remembering the last CTr joint angle during initiation of stance. When, during the pre-stance stage, the CTr joint lowers beyond the last remembered level the searching reflex is triggered (Fig. 7, top). There is a similar behavior and trigger mechanism in insects when the CTr joint load caused by the weight of the leg is not relieved by finding contact with the ground.

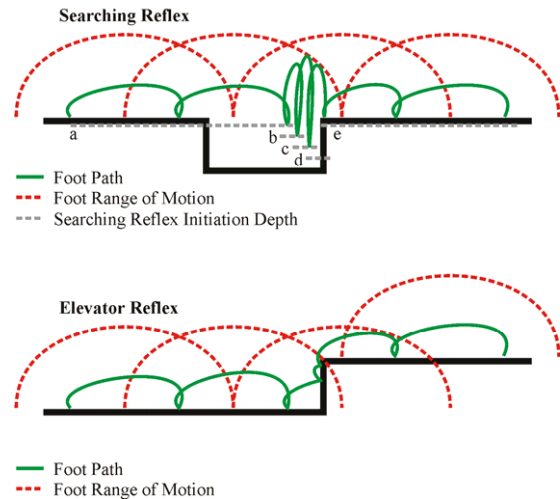


Fig. 7. The searching (top) and elevator (bottom) reflexes temporarily change the joint movement directions in order to navigate past obstacles. Joint directions are changed from their normal motions to become: retraction, levation, and extension. Once the triggering situation is removed (e.g. loss of contact with the obstacle), the normal motions resume. The reflex repeats, as needed, when the triggering situation is detected again. As is shown by the two diagrams, leg movements are limited by the physical range of motion, as indicated by the red dashed line.

As with the elevator reflex, the searching reflex changes the joint movement directions to: retraction, levation, and extension. The levation motion is also done with a higher muscle activation to quickly clear the leg from being below the edge of the gap or hole. This set of altered actions exists briefly when other sensory inputs cause the leg to resume its typical behavior when in pre-stance: protraction, depression, and extension. During the next attempt at locating the ground, the expected ground level is lowered, in case the

terrain is a step down, rather than a gap or hole. The cycle of sensing the lack of ground and initiating the searching reflex continues until ground contact is made.

IV. DESCENDING MODULATION TO ENABLE TURNING

The addition of the hypothesized sensory pathways that enable reflexes broadens the adaptability of the robot to irregular terrain. Another key ability is to allow the robot to turn.

Turning is initiated by a goal-seeking behavior where the robot is attracted to bright lights. Light sources are sensed by two phototransistors mounted on the neck motor and are processed by the microcontroller representing the brain and subesophageal ganglion. The neck motor is actuated in order to balance the light level detected by the two phototransistors, this points the neck toward the light source. The angle of the neck is then used to modulate the muscle activations and motion-changing sensory thresholds for each of the six legs. Altering these values causes the legs to step in different directions without micromanaging leg movements; the local leg controllers are still responsible for moving the leg joints, only the values determining the motion are changed.

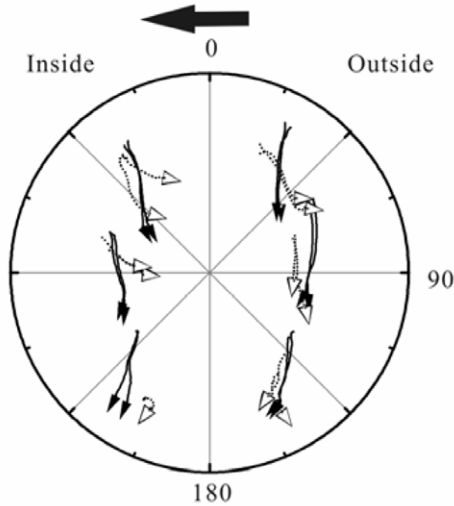


Fig. 8. This figure from [15] shows cockroach foot paths during straight walking (solid lines) and tethered turning (dotted lines) for a tethered animal. Note how the outside legs during turning change very little from straight walking, but inside legs change drastically. These turning foot paths were chosen as the basis for BILL-Ant-a foot paths since they are within the range of motion for the legs. Foot paths of tethered stick insects [7] (not shown) were not chosen as they are not reachable by BILL-Ant-a.

Individual legs have their values changed in order to alter the foot paths based on paths seen in tethered cockroaches during turning (Fig. 8). The foot paths in the figure are reachable paths for the BILL-Ant-a legs and represent the extreme of turning. As the neck moves to track its goal, leg muscle activation and direction changing thresholds are altered proportionate to the amount of neck deflection from center. As the neck moves away from center toward its ± 45 degree limits, the foot paths change from straight walking to

full turning. Experiments showed that the BILL-Ant-a minimum turning radius is approximately 22.0in (55.9cm).

V. REFLEX EXPERIMENTS WITH BILL-ANT-A

Experiments were performed to test the straight walking, elevator, and searching reflex behaviors of BILL-Ant-a. These experiments were conducted on a smooth, flat surface to minimize situations that might spuriously initiate the reflexes. Obstacles were placed in the path of the robot when reflex testing was conducted.

A. Straight Walking Experiment

On a smooth, flat surface without activating the goal-seeking behavior, the robot was allowed to walk using nominal muscle activation and joint direction changing threshold setpoints. This tested the intra-leg joint coordination and inter-leg gait generation behaviors. Speed-dependent gait formation was also tested by increasing the walking speed from full-stop to its highest speed.

During the tests, the robot was able to walk with a maximum speed of 3.0cm/s. This is eight times faster than BILL-Ant-p, which used off-board control, due mostly to the reduction in the communications bottleneck of the serial data cable used to read sensor values and dictate servo motor positions.

When increasing speed from zero to maximum, three series of gait pattern sequences were observed, depending on the starting pose of the legs. As the starting positions of the legs closely resembled an alternating tripod gait, only the alternating tripod gait was observed for all speeds. When the legs were positioned further from that pose, the robot began with a tetrapod gait at slow speeds, and then migrated to an alternating tripod gait as the speed increased. With starting locations completely different from a tripod stance, the robot started with a wave gait, and then transitioned into a tetrapod gait when the speed was roughly 25-30% of maximum. This gait continued until the robot was moving at about 75% of its maximum speed, at which time the gait transitioned into an alternating tripod gait.

B. Elevator Reflex Experiment

A wooden beam was placed in the robot's path in order to initiate the elevator reflex. During the first experiment, a 2.17in (5.0cm) tall, 2.17in (5.0cm) deep beam was placed perpendicularly to the robot's direction of travel. The beam was sufficiently wide such that it could not be navigated around.

BILL-Ant-a normally walks with a step height of approximately 0.5in (1.27cm). The obstacle was easily and repeatedly met with the foot-mounted contact switch. Upon detection of the obstacle, the leg retracted, levated greatly, and extended, as was expected from the elevator reflex behavior. The foot lifted to a height of about 1.75in (4.45cm) before resuming its normal joint directions of protraction, depression, and extension. As this height was insufficient to clear the obstacle, the contact switch again

detected the obstacle and the reflex repeated. This time, starting at a higher elevation, the leg levated to a height of 2.25in (5.72cm), which is the maximum achievable level for the robot. With some scraping of the top surface, the leg was able to surmount the obstacle and BILL-Ant-a successfully navigated over the barrier.

A second experiment with this reflex was conducted with a lower obstacle of the same depth, but only 0.79in (2.0cm) tall. This lower beam was still high enough to trigger the elevator reflex and it was stepped over with only one iteration of the reflex.

Additional trials with lower barriers (less than 0.5in (1.27cm)) did not initiate the reflex, but were navigated with normal stepping.

C. Searching Reflex Experiment

Raised flat, smooth surfaces were placed above another flat surface to create a wide gap, perpendicular to the robot's path of movement, to test the searching reflex behavior.

The first gap tested was approximately 2.36in (6.0cm) deep and 2.17in (5.5cm) across. These dimensions presented difficulty for BILL-Ant-a as the nominal step length is only 3.0in (7.62cm). Success was dependent on the orientation of the legs prior to reaching the gap. When the reflex-initiating leg encountered the gap very late in its pre-stance stage (nearly across the gap), the obstacle was navigated. In other cases, the robot either stumbled across the gap or was unable to navigate the span.

When the gap was narrowed to 1.5in (3.81cm), success was observed in most of the trials. There were a few outstanding cases where the leg was oriented such that it could not reliably retract and then oscillated between retraction and protraction within the gap.

With smaller spans of only 1.0in (2.54cm), the gap was navigated without initiating the elevator reflex since the foot size is 1.0in (2.54cm) square, and the gap was either not seen at all, or the foot was unable to fall into it.

VI. CONCLUSION

The robot presented here, BILL-Ant-a, is the first hexapod to walk using the leg control system identified in the thoracic ganglia of stick insects. This de-centralized joint control network was discovered through insect neurobiology and adapted for use in the legs of the hexapod. Sensory pathways coupling the three joints in a leg are responsible for influencing the direction of each joint such that an emergent, adaptive stepping motion is created. Adaptation is achieved through interaction with the environment, modulation from descending commands, and through the physical coupling of the leg segments that connect the joints.

Additional, hypothesized, biologically-plausible, sensory pathways were also implemented to provide the robot with elevator and searching reflexes, in order to greatly improve the navigation ability of the robot over rough terrain.

Experiments that tested these reflexes showed that the robot could clear raised and lowered obstacles that were beyond the normal stepping heights of the legs, but within reachable levels for the ranges of motion.

The robot completed its tests showing that the network identified in the stick insect thoracic ganglia that coordinates the joints of its legs has been successfully implemented for the first time in a fully autonomous hexapod robot.

REFERENCES

- [1] P. Arena, L. Fortuna, M. Frasca, and L. Patané, "Sensory Feedback in locomotion control," in *Dynamical Systems, Wave-Based Computation and Neuro-Inspired Robots*, Vol. 500, Part II, pp. 143-158, 2008.
- [2] R.D. Beer, H.J. Chiel, R.D. Quinn, K.S. Espenschied, and P. Larsson, "A Distributed Neural Network Architecture for Hexapod Robot Locomotion," in *Neural Computation*, 4, 356-365, 1992.
- [3] R.D. Beer, R.D. Quinn, H.J. Chiel, and R.E. Ritzmann, "Biologically Inspired Approaches to Robotics," in *Communications of the ACM*, Vol. 40, No. 3, March 1997.
- [4] R. Brooks, "A Robot that Walks: Emergent Behaviors from a Carefully Evolved Network," MIT AI Lab Memo 1091, February 1989.
- [5] H. Cruse, J. Dean, U. Müller, and J. Schmitz, "The Stick Insect as a Walking Robot," in *Proceedings of the Fifth Int. Conf. on Advanced Robotics*. Vol. 2, S. 936-940 – ICAR, (1991).
- [6] H. Cruse, T. Kindermann, M. Schumm, J. Dean, and J. Schmitz, "Walknet – a biologically inspired network to control six-legged walking," in *Neural Networks* 11 (1998) 1435-1437.
- [7] V. Dürr and W. Ebeling, "The behavioural transition from straight to curve walking: kinetics of leg movement parameters and the initiation of turning," in *J. Exp. Biol.* 208, 2237-2252, 2005.
- [8] Ö. Ekeberg, M. Blümel and A. Büschges, "Dynamic Simulation of Insect Walking", in *Arthropod Structure & Development* 33 287 (14 pages), 2004.
- [9] K.S. Espenschied, R.D. Quinn, H.J. Chiel, and R.D. Beer, "Biologically Based Distributed Control and Local Reflexes Improve Rough Terrain Locomotion in a Hexapod Robot," in *Robotics and Autonomous Systems*, vol. 18, pp. 59-64, 1996.
- [10] M. Frik, M. Guddat, M. Karatas, and C. D. Losch, "A novel approach to autonomous control of walking machines," in *Proc. of the 2nd Int. Conf. on Climbing and Walking Robots (CLAWAR1999)*, (ed. G. S. Virk, M. Randall & D. Howard), pp. 333-342. Bury St. Edmunds, London: Professional Engineering Publishing Limited, (1999).
- [11] D. Hess and A. Büschges, "Sensorimotor Pathways Involved in Interjoint Reflex Action of an Insect Leg," in *Journal of Neurobiology* 1997; 33(7):891-913.
- [12] W.A. Lewinger, M.S. Branicky and R.D. Quinn, *Insect-Inspired, Actively Compliant Robotic Hexapod*, International Conference on Climbing and Walking Robots (CLAWAR), 2005.
- [13] W.A. Lewinger, B.L. Rutter, M. Blümel, A. Büschges, and R.D. Quinn, "Sensory Coupled Action Switching Modules (SCASM) generate robust, adaptive stepping in legged robots," in *Proc. of the 9th Int. Conf. on Climbing and Walking Robots (CLAWAR2006)*, pp. 661-671, Brussels, Belgium, Sept 12-14, 2006.
- [14] W.A. Lewinger, and R.D. Quinn, "BILL-LEGS: Low computation Emergent Gait System for Small Mobile Robots," in *Proc. of IEEE International Conference on Robotics and Automation (ICRA'08)*: pp. 251-256, Pasadena (CA), USA, May 11-23, 2008.
- [15] L. Mu and R.E. Ritzmann, "Kinematics and motor activity during tethered walking and turning in the cockroach, *Blaberus discoidalis*," in . II Comparative studies on tethered turning and searching," in *The Journal of Comparative Physiology A*, 191:1037-1054, 2005
- [16] L. Mu and R. E. Ritzmann, "Interaction between descending input and thoracic reflexes for joint coordination in cockroach. II Comparative studies on tethered turning and searching," in *The Journal of Comparative Physiology A*, 194:299 – 312, 2008.