PERFORMANCE REPORT

A Cockroach-Like Hexapod Robot for Natural Terrain Locomotion

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Period of Performance: 3 Years

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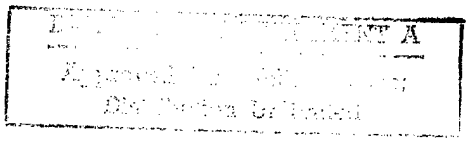

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Research Progress

The posture controller for Robot III was found to be robust to large disturbances and modeling errors. It was discovered that the 48 valves controlling the robot have dissimilar outputs by as much as 30%. We had initially assumed that the valves were similar and used one model for all of the valves. This dissimilarity caused the magnitudes of some control torques to be 30% less than desired. The middle legs, which typically bear much of the load, were particularly affected. Despite this the posture controller worked well in rejecting large disturbances. We have now experimentally modeled all of the valves and implemented the models in the controller.

In our initial work with Robot III walking, the robot's posterior swayed when legs were lifted in the transition to swing. In cockroach rear legs, the coxa-femur joint and femur-tibia joint typically move in-phase with the same magnitude. We designed the robot with 3 degrees of freedom (DOF) in case all 3 were found to be important. We have now reduced them to 2 DOF by disconnecting the femur-tibia actuators and kinematically coupling the C-F and F-T joints using a parallel four-bar mechanism. This causes the joint coupling observed in the animal and reduces swaying of the robot's posterior as it walks.

The posture controller forms part of a locomotion controller. The posture controller produces joint torques in the stance legs to cause a desired body motion. Additional controller components are necessary. We are developing a motion generator for swing legs to cause them to return to their anterior extreme position (AEP). The stick insect leg coordination mechanisms are being used as a gait controller. The strain gages mounted on the proximal ends of the tibias are now being used as contact sensors to determine the transition from swing to stance. This is important because the posture controller needs to have knowledge of which legs may be used to support the body.

An adaptive pattern generator has been developed. The leg controller learns the joint motions required to cause the foot to follow a model path without using an explicit inverse kinematics solution. It adapts to load and changes in its environment. In his visit to CWRU, Pearson described a pattern generator found in cat locomotion that adapts to damage in the leg's physiology.

Reducing loading on the middle legs of the cockroach causes a switch from the tripod gait to search movements. This change has been characterized in detail and we have begun to perform intracellular recordings in order to develop an understanding of the neural basis of this switch between walking and searching. We have also been studying the postural and walking effects of lesioning neck connectives in the cockroach. While the insect experiences significant difficulties in posture and walking immediately after the lesion, some of these problems are alleviated in approximately two weeks time.

We have begun to mathematically analyze phase-locking in the stick-insect-based gait controller that we have utilized in our robots. As a first step, we have almost completely analyzed the asymptotic relative phase produced by two oscillators coupled in one direction by a single coupling mechanism. We have derived analytical return maps and analytically characterized the layout of these return maps in parameter space. We have also derived analytical asymptotic relative phase maps for particular cases, and used these maps to derive analytical boundaries between regions of different asymptotic relative phase density. This analysis completely accounts for the phase boundaries observed in simulations of this 2-oscillator system.

A model of tongue biomechanics which has been used for studying the neural control of muscular hydrostatic structures was coupled to model continuous time recurrent neural networks that were "evolved" using genetic algorithms. These neural networks successsfully controlled a rhythmic lapping behavior. Analysis of the resulting networks indicated that during certain phases of the behavior, details of the biomechanics of the periphery were critical for determining properties of the neural network. In contrast, during other phases, the biomechanics did not significantly constrain the operation of the neural network. These studies may have implications both for biological tongues, and for the design of controllers for hydrostatic robots.

Publications

Bachmann, R. J., Nelson, G. M., Flannigan, W. C., Quinn, W. C., Watson, J. T., Tryba, A. K., Ritzmann, R. E. (1998). "A Robot Based Upon Cockroach Biomechanics," IASTED International Conference, Robotics and Manufacturing (RM'98), Banff, CA, July 26-29, 1998.

Beer, R.D., Chiel, H.J. and Gallagher, J.C. (submitted). General principles and individual variability in evolved model CPGs for walking: Neural and biomechanical constraints. Submitted to *J. Neurophysiology.*

Beer, R. D., Chiel, H. J., and Gallagher, J. G. (1998). Analysis of evolved model central pattern generators for walking. 1998 Annual Meeting of the Biomedical Engineering Society.

Beer, R. D, Chiel, H. J., and Gallagher, J. G. (1998). Evolution and analysis of model central pattern generators for walking. *Fifth International Congress of Neuroethology.*

Birch, M. C., Quinn, R. D., Zill, S. N., Ritzmann, R. E. (1998) "A Model Cockroach Leg for Sensori-motor Studies," *The Fifth International Congress of Neuroethology*, August 23-28, 1998.

Chiel, H.J., Beer, R.D. and Gallagher, J.C. (submitted). Dynamical modules in an evolved model CPG for walking. Submitted to *J. Neurophysiology.*

Endo, Y. (1998). "Development of a Model Car for Implementation of Crash Avoidance System," M.S. Thesis, January, 1998.

Flannigan, W. C. (1998). "Finite Element Modeling of Arthropod Skeleton," M.S. Thesis, 1998.

Flannigan, W. C., Nelson, G. M. and Quinn, R. D. (1998). "Locomotion Controller for a Crab-like Robot," *1998 IEEE International Conference on Robotics and Automation (ICRA'98)* Proceedings, presented May 1998, Leuven, Belgium.

Kolacinski, R., M. and Quinn, R. D. (1998). "Design and Mechanics of an Antagonistic Biomimetic Actuator System," *1998 IEEE International Conference on Robotics and Automation (ICRA'98)* Proceedings, presented May 1998, Leuven, Belgium.

Kolacinski, R. M. and Quinn, R. D., (in press). "An Antagonistic Biomimetic Actuator System," *Robotics and Autonomous Systems.*

Nelson, G. M., Bachmann, R. J. Quinn, R. D., Watson, J. T., Tryba, A. K., Ritzmann, R. E. (1998). "A Cockroach-like Robot," *1998 IEEE International Conference on Robotics and Automation* (ICRA'98) Video Proceedings, presented May 1998, Leuven, Belgium.

Nelson, G. M. and Quinn, R. D. (1998). "Posture Control of a Cockroach-like Robot," *1998 IEEE International Conference on Robotics and Automation (ICRA'98)* Proceedings, presented May 1998, Leuven, Belgium.

Nelson , G. M., Quinn, R. D., Bachmann, R. J., Watson, J. T., Tryba, A. K., Ritzmann, R. E. (1998). Posture Control of a Robot with Cockroach Mechanics, *The Fifth International Congress of Neuroethology*, August 23-28, 1998.

Quinn, R. D. and Ritzmann, R. E., "A Bio-Robotics Strategy that leads to Advances in Robotics and Biology, submitted to *Connection Sciences*.

Quinn, R. D., Ritzmann, R. E. (1998). A Hexapod Robot based upon Cockroach Mechanics, *The Fifth International Congress of Neuroethology*, August 23-28, 1998.

Schaefer, P.L., R.E. Ritzmann (1998). Supraoesophageal influence on the thoracic circuitry of cockroach escape *The Fifth International Congress of Neuroethology*, August 23-28, 1998.

Tryba, A.K., R.E. Ritzmann, (1998). A robust and reversible preparation for examining the neural architecture underlying searching and walking in the cockroach, *Blaberus discoidalis. The Fifth International Congress of Neuroethology*, August 23-28, 1998.

Vaidyanathan, R., Chiel, H. J., and Quinn, R. D. (1998). "A Hydrostatic Robot for Marine Applications," *1998 IEEE International Conference on Robotics and Automation* (ICRA'98) Video Proceedings, presented May 1998, Leuven, Belgium.

Watson , J.T. , A.J. Pollack, S.N. Zill, R.E. Ritzmann, (1998). Kinematics and leg muscle activity in cockroaches climbing over obstacles. *The Fifth International Congress of Neuroethology*, August 23-28, 1998.

Watson, J.T. and R.E. Ritzmann (1997). Leg kinematics and muscle activity during treadmill running in the cockroach, Blaberus discoidalis: I. Slow running. *J. Comp. Physiol . A.* **182:**11-22.

Watson, J.T. and R.E. Ritzmann (1997). Leg kinematics and muscle activity during treadmill running in the cockroach, Blaberus discoidalis: II. Fast running. *J. Comp. Physiol . A.* **182:**23-33.

Presentations

R. Beer gave an invited seminar at the Navy Center for Applied Research in Artificial Intelligence, Washington, D.C., March, 1998.

R. Beer was an invited participant in the Workshop on Neuro-Mechanical Interactions, Santa Fe Institute, Santa Fe, NM, April 3-5, 1998.

R. Beer was an invited speaker at the Workshop on Animal Locomotion and Robotics in the Emerging Applications of Dynamical Systems Program at the Institute for Mathematics and its Applications, University of Minnesota, Minneapolis, Minnesota, June 1-5, 1998.

R. Beer gave a talk at the ONR Legged Locomotion/Muscle-Like Actuators Workshop, Indian Head, Maryland, May 19-20, 1998.

H Chiel gave a Biology Dept. seminar at CWRU on April 23, 1998.

Y. Endo defended his M.S. Thesis "Development of a Model Car for Implementation of Crash Avoidance System" in January, 1998.

W. C. Flannigan defended his M.S. Thesis "Finite Element Modeling of Arthropod Skeleton" in April, 1998.

W.C. Flannigan gave a Mechanical and Aerospace Engineering seminar in April, 1998.

R. Quinn gave a talk at the ONR Legged Locomotion/Muscle-Like Actuators Workshop, Indian Head, MD, May 19-20, 1998.

R. Quinn spoke in the Ohio Aerospace Institute Summer Lecture Series, June, 1998.

R. Ritzmann gave a seminar to "Young Scholars Grand Symposium" at CWRU on January 17, 1998.

R. Ritzmann, gave a Biology Department seminar at CWRU on January 22, 1998.

R. Ritzmann gave an invited seminar to the Kirtlandia Society of Cleveland on March 14, 1998.

R. Ritzmann gave a talk at the ONR Legged Locomotion/Muscle-Like Actuators Workshop, Indian Head, MD, May 19-20, 1998.

R. Ritzmann gave an invited seminar at Ohio University on May 27, 1998.

Bio-Robotics Lab personnel: "Biologically-Inspired Robotics at CWRU," CWRU open houses and other group tours for high school students and "Friends of the University", April 1998.

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