PERFORMANCE REPORT

NEURAL NETWORKS FOR REAL-TIME SENSORY DATA PROCESSING AND SENSORIMOTOR CONTROL

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1. Experimental Work

In our experimental work over the past six months we have again made progress in both the behavioral and physiological areas. Behaviorally, we have continued our efforts to define the effects of leg deficits. In physiological experiments, we have documented the relative timing of wind evoked activity in individual ventral giant interneurons (vGIs).

We have performed behavioral observations both on whole leg ablation and on animals that have received lesions of specific proprioceptors of the mesothoracic legs. High speed video data clearly demonstrated that both of these procedures altered the escape movements. However, the changes that were observed were not consistent from animal to animal. In the leg ablation procedures, we found that removal of mesothoracic legs initially caused the animal to simply escape forward. This is consistent with our observations on intact animals that indicated that much of the turning direction comes from the actions of the mesothoracic legs. Nevertheless, when we retested the animals three and five days after the ablation, some of the turning ability returned. We then moved the system to the tethered preparation where we could obtain more direct information on leg movements. It was our hope that this could explain the changes seen in the free ranging animal. However, the results were not completely consistent. As with the free ranging animals, on the day of the ablation the metathoracic legs simply extended backward, and on the third day there was an increase in trials in which the contralateral leg moved forward. This could account for the return to turning ability. However, on the fifth day the leg movements appeared to be intermediate between the first and second day conditions.

There are at least two possible explanations for the inconsistencies in these data. First, they could represent real differences in the population of animals tested. We have now retested a single set of animals in both setups, and found similar results. The second explanation is that the inconsistencies could represent real differences in the free ranging and tethered paradigms. One potentially critical factor is that in the tethered preparation the animal is not supporting its own weight. Also, since the animal's legs are actually slipping rather than making effective movements, it is possible that the leg movements are substantially altered. Although a problem in interpreting these results, the differences in the two paradigms may actually prove to be useful tools in understanding principles of the turning movement, if we can quantify the effects. For this reason, we plan to spend more time comparing leg movements in the two paradigms.

In physiological investigations, a graduate student who is supported by the ONR grant, Songhai Chai, is completing a study of the relative timing of the various vGIs within wind responses from various different directions. In order to model the transfer of information from vGIs to thoracic interneu ns, we must not only know which vGIs connect to each thoracic interneuron but also when the vGI activity activates those cells. The relative timing of vGI action potentials within wind puffs could change in a systematic fashion along with wind angle. Relative latency could then contribute to the directional properties of the system. To measure temporal relationships, Songhai Chai has recorded from vGIs intracellularly in pairs. Once two vGIs are impaled, standard wind puffs are presented to the animal from various different directions. The relative latency of the two vGIs can then be determined for wind from different directions and plotted on polar graphs. His findings indicate that all of the vGIs arrive within a similar time frame. That is, the information from each vGI is factored into the initial response of the TIAs. This includes GI 4, which is significantly smaller in diameter than the other vGIs. Left and right GI1s, which have directional biases relative to number of action potentials are also biased in their latency. So a left GI1, which responds to wind from the left with more action potentials than would right GI1, also responds with a shorter latency. This should enhance the left-right directional effect that GI1s have upon TIAs. This information will be incorporated into the computer model as we attempt to determine the inputs responsible for wind fields of individual TIAs.

2. Modeling and Simulation

Using the experimentally measured vGI firing curves that we reported previously, we studied the effects of these nonlinear responses on an existing linear model of the vGI windfields developed by Daley and Camhi (*J. Neurophysiol.* **60**). For the most part, we found that the ability of their model to account for the overall directional biases of the vGI is still valid. However, we were able to show that, if the vGI thresholds to wind are comparable to their thresholds to intracellular current injection, the saturation of the firing curves severely weakens their directional bias predictions. In addition, we demonstrated that the vGI windfields produced by their model are sensitive to the models chosen for the cercal wind responses. These findings suggest that both the thresholds of the vGIs to wind and the detailed shapes of the cercal windfields may need to be better characterized before models of the vGI windfields can be fully evaluated.

While Daley and Camhi's model can explain the overall directional biases of the vGIs (subject to the difficulties discussed above), it cannot quantitatively account for the detailed shapes of the vGI windfields under both normal and lesioned conditions. We have been able to produce vGI models which circumvent this problem using backpropagation constrained by the following data: (1) the known signs and connectivity from the cercal hair columns; (2) the experimentally determined average firing curves for each of the vGIs; (3) the normal wind-responses of each vGI; (4) the wind responses of vGIs 1, 2 and 3 following ipsilateral cercal ablation. These models build upon earlier backpropagation models which were less fully constrained by the experimental data. Our current models can reproduce both the normal and lesioned vGI windfields in a way consistent with the observed firing properties and cercal-to-vGI connectivity.

Next, we turned to applying this model to the vGI to an examination of the way in which the cercal-to-vGI connections can adapt to a missing cercus. By ablating a model cercus and then retraining the lesioned network to reproduce the experimental observed vGI windfield recoveries, we can model this adaptation process. Under these conditions, we have found that backpropagation can effect a vGI windfield recovery similar to that observed in the animal. Examining the resulting changes in connection strengths, we have found that very small changes are sufficient to account for the recovery process, and that these changes are distributed fairly uniformly across the available connections.

A new version of our body simulation software has been developed. The most significant feature of this new version is that it can accept input from a variety of sources. For example, we now have the capability of driving the three-dimensional body model from digitized data from a high speed video camera, allowing us to animate digitized escape turns and to view them from any perspective. We are currently connecting our simulation system to a legged dynamics model developed by Roger Quinn and a graduate student. Eventually, this will result in a fully dynamic model of the cockroach body.

We are also attempting to extend our current vGI models to incorporate the actual time of occurrence of individual spikes. Currently, we are applying genetic algorithms to the problem of fitting the parameters of a Getting-type integrate and fire model to the vGI spike train data. Several preliminary models have been generated in this fashion.

3. Robotics

We have traced the differences in cross-body phasing between the robot and the original locomotion simulation to asymmetric delays in the interface electronics and motor responses. Adjusting the stiffnesses of the position controllers in each leg to compensate for these differences has enabled us to reproduce in the robot the complete range of gaits observed previously in simulation. In addition, through a variety of lesion studies, we have shown that the locomotion controller exhibits a similar robustness in the robot as it did in simulation.

Recently, we have been exploring a non-neural approach to biologically-inspired hexapod locomotion control. We have implemented a variety of leg influence rules that Cruse and his colleagues (*TINS* **13**:15-21) have identified in the walking stick insect in our robot. Our preliminary results indicate that these mechanisms are also capable of robustly producing the full range of statically stable hexapod gaits.

Publications

Beer, R.D., Kacmarcik, G.J., Ritzmann, R.E. and Chiel, H.J. (1991). A model of distributed sensorimotor control in the cockroach escape turn. In R.P. Lippman, J. Moody and D.S. Touretzky (eds.) *Advances in Neural Information Processing Systems 3* (pp. 507-513). Morgan Kaufmann Publishers.

Beer, R.D., Chiel, H.J., Quinn, R.D., Espenchied, K. and Larsson, P. (in press). A distributed neural network architecture for hexapod robot locomotion. To appear in *Neural Computation.*

Ritzmann, R.E., Pollack, A.J., Hudson, S. and Hyvonen, A. (1991). Convergence of multimodal sensory signals at thoracic interneurons of the escape system of the cockroach, *Periplaneta americana. Brain Research* **563**:175-183.

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Chiel, H.J. and Beer, R.D. (in press) Simulation of adaptive behavior. To appear in *Current Opinion in Neurobiology* **1**(4).

Chiel, H.J. and Beer, R.D. (in press). Neural and peripheral dynamics as determinants of patterned motor behavior. To appear in D. Gardner (Ed.), *The Neurobiology of Neural Networks*. MIT Press.

Chiel, H.J., Beer, R.D., Quinn, R.D. and Espenschied, K. Robustness of a distributed neural network controller for a hexapod robot. Conditionally accepted for publication in *IEEE Transactions on Robotics and Automation.*

Nye, S.W. and Ritzmann, R.E. Motion analysis of leg joints associated with escape turns of the cockroach, *Periplaneta americana.* Submitted to *J. Comp. Physiol. A.*

Beer, R.D. and Gallagher, J.C. Evolving dynamical neural networks for adaptive behavior. Submitted to *Adaptive Behavior.*

Quinn, R.D., Beer, R.D, Chiel, H.J., Espenschied, K and Larsson, P. Biologically-inspired neural control of a mechanical hexapod. Submitted to *ASME J. of Dynamic Systems, Measurement and Control.*

In Preparation

"Reconstruction of Ventral Giant Interneuron Windfields in the Cockroach Using Constrained Backpropagation," by Randall D. Beer, Gary J. Kacmarcik, Songhai Chai, Roy E. Ritzmann, and Hillel J. Chiel.