Neuroinformatics

1539-2791/05/167–170/$30.00
DOI: 10.1385/NI:3:3:167

Editorial

Neurorobotic Models in Neuroscience and Neuroinformatics

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In July 2004, for the first time in several years, the International Conference on the Simulation of Adaptive Behavior returned to America (Santa Monica, California; for details *see* www.isab.org/sab04/). As part of this prestigious meeting, which draws participants from both the natural and the artificial sciences, we had the great pleasure of hosting the workshop entitled: "Neurorobotic Models in Neuroscience and Neuroinformatics."

Adaptive behavior in biological organisms results from interactions among brains, bodies, and environments. Our workshop provided a forum for discussing neurorobotic approaches to understanding these interactions. A key feature of the neurorobotic approach is the incorporation of features of neuroanatomy and neurophysiology that allow comparison with empirical data. A neurorobotic device has the following properties:

- It engages in a behavioral task.
- It is situated in a structured environment.
- Its behavior is controlled by a simulated nervous system having a design that reflects, at some level, the brain's architecture and dynamics.

As a result of these properties, neurorobotic models provide heuristics for developing and testing theories of brain function in the context of phenotypic and environmental interactions. Also, neurorobotic models may provide a foundation for the development of more effective robots, based on an improved understanding of the biological basis of adaptive behavior.

The workshop was arranged around 11 invited presentations in a single day, with plenty of time reserved for informal discussion. Presentations were organized into four separate sessions: motor control and locomotion, hippocampus and memory systems, reward systems and action selection, and neurodynamics. With the sessions arranged in this order, the overall trajectory of the day was toward greater

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abstraction in the topics discussed. Participation at the workshop numbered between 40 and 50, comprising invited experts, registered participants, and those who had succumbed to the intense marketing effort during the preceding meeting.

Motor Control and Locomotion

This first session aimed at exploring and discussing how robots can be used as tools to test models of animal locomotion and motor control. Recent years have witnessed a developing consensus that locomotion is organized in terms of dynamic pattern generators modulated by sensory feedback. The talks in this session expanded on this theme with a striking diversity. Hiroshi Kimura (Tokyo, Japan) opened the meeting by arguing that neurorobotics can provide a bridge between neuroscience and biomechanics. This argument was illustrated with a series of studies on emergent-legged locomotion, based on a central pattern generator mechanisms modulated by reflexes. Stefan Schaal (Los Angeles, CA) discussed behavioral, imaging, and modeling evidence suggesting that the concept of a dynamic pattern generator could be extended to limb movement in primates. He introduced a model of a *learnable* pattern generator and demonstrated its viability using a series of synthetic and humanoid robotic examples. The final talk in the session, from Auke Ijspeert (Lausanne, Switzerland; with Crespi), described recent achievements in the construction of an amphibious salamander-like robot. The salamander is capable of both swimming and walking, and therefore represents a key stage in the evolution of vertebrate-legged locomotion. Ijspeert and coworkers have developed models based on coupled neural oscillators with proprioceptive and sensory feedback, to reproduce the salamander's typical swimming and walking gaits. A neurorobotic implementation was found necessary for (1) testing whether the models could produce locomotion both in water and on ground and (2) investigating how sensory feedback affects dynamic pattern generation.

Hippocampus and Memory Systems

As has long been the case in neuroscience, a major theme in neurorobotics is the role of the hippocampus and associated areas in memory and navigation. The second session of the workshop moved the focus to this more "central" problem of the nervous system. Angelo Arleo (Paris, France; with Boucheny, Degris, Brunel, and Wiener) began by discussing the "head direction" system of the rat, which is closely coupled to the hippocampus and which provides a likely substrate for the rat's "sense of direction". Arleo and his coworkers have utilized both experimental (i.e., extracellular recordings) and theoretical (i.e., neurorobotic modeling) approaches to test the hypothesis that the head-direction system relies on dynamic visual signals (for e.g., motion parallax) to select among visual landmarks that serve as anchors. Their neurorobotic implementation was able to reproduce the experimental observations as well as suggesting roles for inertial self-motion signals. Phillipe Gaussier (Cergy, France; with Cuperlier, Quoy, Banquet, Boucet, and Save) presented a model exploring how the hippocampus, the prefrontal cortex, and the basal ganglia may be connected in a network enabling a variety of navigation behaviors. Their model suggested an important distinction between "place cells", which respond preferentially in particular regions of the environment, and "place transition cells", which may link place cell activity with the triggering of motor actions. In the last talk of the session, Jeff Krichmar (San Diego, CA; with Seth, Nitz, Fleischer, and Edelman) introduced Darwin X: A "brain-based device" incorporating a large-scale simulation of the hippocampus and surrounding areas. Darwin X was able to solve a dry version of the Morris "water-maze" task by integrating visual and self-movement cues. A novel time-series analysis technique was employed, based on

"Granger causality," as a means of identifying different functional pathways in the hippocampus and their influence on behavior.

Reward Systems and Action Selection

After lunch, the workshop continued its trajectory in the direction of abstraction with a series of talks on reward systems and action selection: How do animals choose what to do next? How are their choices influenced by value, feedback, reinforcement, or punishment? Kenji Doya (Kyoto, Japan) described recent progress in the "Cyber-rodent" project, in which two-wheeled rodent-like robots move autonomously in an environment containing scattered battery packs. These robots can exchange control parameters with each other via infrared communication ports. Doya reported some preliminary results from this project, including the evolution of meta-parameters for reinforcement learning and the emergence of reward and cost functions. Ricardo Chavarriaga (Lausanne, Switzerland; with Gerstner) presented a model of reward-based selection of navigation strategies. Their model incorporated two navigation strategies; one based on hippocampal learning of spatial representations, and the other based on striatal learning of a taxon strategy for approaching visual goals. Results from the model complemented neurobehavioural studies, which have indicated that rats select a reward-maximizing navigation strategy according to the situation in which learning occurs. Last, Will Alexander (Bloomington, IN) described a neurorobotic model of neuromodulation during learning of appetitive and aversive events. When the occurrence of rewarding events was controlled by the experimenter, the model reproduced salient features of the mammalian dopamine system. When the occurrence of reward was the result of autonomous behavior, the model provided a picture of complex interactions among environmental properties, behavior, and synaptic development, including structuring of the environment by the agent.

Neurodynamics

The final session of the day moved beyond models of particular brain systems or behaviors altogether, to tackle instead the fundamentals of neuronal dynamics. Olaf Sporns (Bloomington, IN; with Lungarella) illustrated the insights gained by a variety of statistical and information-theoretic methods into the structuring of sensory input by self-movement. Application of these measures to computer simulations, as well as to an active vision robotic system, supported their suggestion that the ability to actively generate statistical regularities in sensory data represents a major functional rationale for the evolution and design of embodied systems. The last talk of the workshop was given by Steve Potter (Atlanta, GA), who described the latest developments in "hybrots": hybrids of living neurons and robots. The aim of this project is to study learning and memory in vitro, by culturing mouse cortical neurons and glia on a multielectrode array. The culture is then connected to a robotic phenotype which is both controlled *by* the culture and which provides stimulus inputs *to* the culture. To leverage the in vitro character of this preparation, Potter and coworkers have applied 2-photon laser-scanning microscopy to observe morphological dynamics at a variety of time scales.

Conclusion

The meeting concluded with a general discussion which reflected that the day had provided a great deal of intellectual stimulation, thanks in large part to the excellence of the invited talks, and had strengthened the belief of many that neurorobotic modeling is an indispensable and uniquely insightful method in the new neurosciences. This view was even shared by some participants without previous exposure to neurorobotics, whose attendance was the result of earlier salesmanship. Although varied in their experience with neurorobotics, the participants, all experts in their own right, were uniformly incisive and enlightening during the question and discussion periods, and the workshop could not have been successful without their involvement. Indeed, the discussion carried on well past the scheduled close of the meeting, finally petering out in the small hours of the following day in the back room of the King's Head in downtown Santa Monica. For even in Los Angeles, a good British pub is the only place for these things.

The present Special Issue contains a set of papers based on a selection of the presentations described above. We are very grateful to the editors of *Neuroinformatics* for preserving and disseminating the scientific content of the workshop by publishing these articles. Although not all speakers are represented, we have included papers reflecting each of the four themes, and we believe that their combination in a single volume will serve the same purpose for the readership of *Neuroinformatics* that the workshop served for its attendees: To reveal neurorobotic modeling as a central methodology in the neurosciences of the 21st century.

Acknowledgments

We thank Auke Ijspeert and Ricardo Chavarriaga for their help in the organization of the workshop, as well as for their excellent contributions to this Special Issue. We are very grateful to the organizing committee of SAB04 for supporting our workshop proposal, for providing a stimulating environment for it to take place, and also for encouraging a healthy participation. We thank the Neurosciences Research Foundation for funding. We are particularly grateful to Giorgio Ascoli for his support and encouragement, and especially for his advice on editorial matters.