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Methods & Applications

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Introduction

Thomas R. Consi and Barbara Webb

Animals have long served as inspiration to roboticists. Their adaptability, flexibility of motion and great variety of behaviors has made them the (often unspoken) benchmarks for robot performance. Beyond inspiration, however, animals have not always yielded much in the way of concrete mechanisms that could be used to build robots, and robots have been almost comical representations of animals. The problem was that engineered components did not have the performance or form factor of their biological counterparts. Recently things have begun to change and robots are now capable, to a limited degree, of accurately mimicking the behavior of animals. Advances that have made this possible include microprocessors of ever increasing computational power and ever decreasing size, tiny solid-state sensors, low-power electronics, and miniaturized mechanical components. Robots can now be built that have some of the sensing capability of, for example, a desert ant or the motor skills approaching that of a cockroach. Animal-like robots (termed biorobots in this book but also known as biomimetic or biomorphic robots) are serving an increasingly important role as a link between the worlds of biology and engineering.

Biorobotics is a new multidisciplinary field that encompasses the dual uses of biorobots as tools for biologists studying animal behavior and as testbeds for the study and evaluation of biological algorithms for potential applications to engineering. There have been several recent reviews of biorobotics as a way to apply biological algorithms and mechanisms to engineered systems (e.g. Beer et al. 1993, Dario et al. 1993, Hirose 1993, Srinivasan and Venkatesh 1997, Bekey 1996, Beer et al 1997, Sharkey and Ziemke 1998, Chang and Gaudiano 2000) This book particularly concerns the role of robots as tools for biologists, a more recent phenomenon. Understanding how animals work is essentially a problem of "reverse engineering" i.e. rather than building something with a certain functional capability, we have something with a certain functional capability and want to work out how it works. Thus the application of engineering methodologies for modeling animals seems an appropriate and promising approach. However such a task is far from easy.

An animal can be described as mobile vehicle with a multimodal, high-bandwidth interface to its environment. One merely has to look at a cricket with a hand lens to see the thousands of sensory hairs studding its exoskeleton. Each hair is invested with many sensory cells and different types of cells "see" the environment in different ways (e.g. some respond to mechanical stimulation and others to chemical signals). Animals are therefore, deeply embedded in their environments and they are profoundly affected by the subtle and complex signals within those environments (e.g. turbulence, polarization patterns, acoustic noise, thermal micro-climates, etc). It is the complexity of the environment and the high degree to which animals can sense and respond to that complexity that makes it difficult to obtain a detailed understanding of the world as seen by an animal through its senses and interpreted through its behaviors. The situation is made even more complicated because the animal invariably disturbs its environment and creates a new set of stimuli that may also be important to the creature's behavior.

Biorobots are now enabling biologists to understand these complex animal-environment relationships. They can be thought of as micro-environment exploration robots that can detect and map sensory signals at the level of the animal and can measure how the presence and motion of the animal affects those signals. This data, coupled with observations of the animal itself, can lead to very sophisticated hypotheses as to what is causing a behavior and what is shaping the behavior as it plays out. These hypotheses can then be tested in laboratory or field-based experiments with the biorobot robot as well as with the real animals. The robot offers two distinct advantages over the real animal in such studies. First, the behavior under test in the robot is not affected by competing, uncontrolled, behaviors. Second, orders of magnitude more data can be obtained from a robot, compared to an animal, on its actions, its sensory input, and its internal states. Despite these advantages it must not be forgotten that the biorobot, however sophisticated, is only mimicking part of the animal. Biorobotics is a tool-based discipline, much like the microscopy, and one should never lose sight that biorobots are tools for use in studies of animals, not replacements for such studies.

Computer simulation has long been another tool used by biologists to model biological phenomena at all levels of organization, from populations of animals to individual creatures, to "subassemblies" such as the ear, down to individual components, neurons, sensory receptor cells and muscle fibers. The question naturally comes to mind as to why bother building robots at all when computer/numerical models have been so useful? The answer to this question comes from the complexity of the sensory world discussed above. A hypothesis implemented on a robot operating in a real environment can be tested more rigorously than in simulation because the hypothesis will be challenged with real, complex and often unmodelable stimuli. For example, hydrodynamic simulations of underwater turbulence are very complex yet still do not adequately represent real turbulent flow. This type of flow is what shapes the olfactory signal sensed by lobsters, fish and many other underwater creatures. It is far easier and cheaper to generate a real odor plume to test a plume following algorithm than to use a plume simulation that will produce an inferior stimulus compared to the real thing. Biorobots can be usefully thought of as physical models of animals that enable a level of investigation beyond that possible with simulation. Note that biorobots do not replace simulation, just as they do not replace real animals in experiments. Simulation is very useful both as a hypothesis testing methodology and as a design tool for developing biorobots. It often happens that there is a cyclic iteration of animal observations, simulations, and biorobotic experiments during the course of an investigation that, in the best case, leads to an increasingly more accurate picture of the animal's behavior and its physiological underpinnings.

A Brief History of Biorobotics

The attempt to make machines behave in a lifelike manner is as old as science (De Solla Price 1964). Ingenious mechanical devices have been built to mimic animal behaviors, sometimes with impressive detail e.g. Vaucanson's duck (de Vaucanson 1738, Chapuis and Droz 1958). However their clockwork mechanisms did not noticeably resemble the inner workings of biological systems. A more or less direct scientific lineage to biorobotics can be traced starting at the end of the nineteenth century with the advent of the then new discipline of electrical engineering. Nikola Tesla conceived "the idea of constructing [an] automaton that would … respond, as I do myself, but of course, in a much more primitive manner, to external influences. Such an automaton evidently had to have motive power, organs for locomotion, directive organs, and one or more sensitive organs so adapted to be excited by external stimuli…." He built and demonstrated a radio controlled boat in the 1890s and discussed plans for an automaton that "will be able, independent of an operator, left entirely to itself, to perform, in response to external influences affecting its sensitive organs, a great variety of acts and operations as if it had intelligences [sic]" (cited in Rosheim 1994). The pioneering physiologist Jacques Loeb compared the behaviors of "lower" animals to that of an artificial heliotropic machine, a light following device made of motors, photocells and relays (Loeb 1918). Breder (1926) developed two model boats, one propelled by a flapping fin and the other by an undulating fin, to study fish propulsion. Fifty years ago the advent of cybernetics saw the building of a series of electromechanical devices intended to explore aspects of animal behavior, such as the "homeostat" machine (Ashby 1952) and the reactive "turtle" (Walter 1961). A number of similar devices built around this time are described in Young (1969).

Although the advent of modern transistor technology and computers might have been expected to support rapid further progress in building animal-like robots, in fact the main research emphasis diverged in somewhat different directions. One might be termed investigation of the "disembodied" brain: an emphasis on building machines with human reasoning powers (artificial intelligence) rather than human (or animal) physical powers. Although some of these mechanisms were "biologically-inspired," such as the neural network approach, the tasks investigated were still largely cognitive. Even within biology, where "analog" (i.e. electrical circuit models) of hypothesized animal control systems continued to be used as simulation tools (e.g. Harmon 1961, Collewijn 1972; Collett 1980) till replaced by today's software simulations, the systems rarely "closed the loop" with real actuators and sensors. On the other hand, investigation of the *physical* problems of sensing and control for artificial systems were somewhat subsumed by mechanization, with much robot research deriving from industrial concerns (with the main exception some notable research on humanoid robots in Japanese research groups such as that of Ichiro Kato). Cybernetic theory for operating these systems developed sophisticated mathematical formalisms, but was in the main not closely related to biology. One reason may have been the limited understanding of how biological systems actually worked.

Thus a parallel development in biology that was critical to the emergence of biorobotics was the application of control system theory and other engineering techniques to the study of animal behavior, most notably by the "European School" of neuroethology. This work was primarily focused on the sensory-motor behavior of arthropods and began with the work of von Holst and Mittelstaedt (reviewed in Schone 1984). Ground breaking studies on many arthropod systems were carried out in the mid to latter twentieth century. A few examples of the many systems studied include: fly vision (reviewed in Buchner 1984), ant navigation (Wehner 1989), walking in the stick insect (Cruse 1990) and crab oculomotor behavior (Horridge and Sandeman 1964). This work, and other similar studies, provided a rich baseline of quantitative data on the performance of animals that was ready to be incorporated into the biorobots that began to emerge in the last decades of the twentieth century.

Two notable event in the development of current biorobotics were the publication of the slender volume *Vehicles, Experiments in Synthetic Psychology* (Braitenberg 1984) and the emergence of behavior-based robots (Brooks 1986a). Braitenberg in "Vehicles" showed how animal-like behaviors might be produced in simple "thought" robots and how these vehicles may be used to interpret behavioral data. Brooks and colleagues expanded the field of artificial intelligence to consider the problems faced by relatively simple insect-like robots that must navigate within the real world. Other influential work done in this period includes the highly impressive running robots developed at the Massachusetts Institute of Technology's Lego Lab (Raibert 1986), and the application of Arbib's (1972) biologically based "schema theory" to autonomous robots by Arkin (1987). The fields of artificial life (Langton 1989) and adaptive behavior or "animats" (Meyer and Guillot 1990) also emerged around this time, with their emphasis on artificial replication of precognitive behaviors, though still largely in simulation. What these interdisciplinary movements helped generate was a meeting point between robot technology on one hand and mainstream biological models on the other.

This has resulted in recent years in a rapid increase in the number of models of specific animal competencies being implemented in robot devices, driven both by advances in technology, as mentioned above, and in our expanding knowledge of the sensory, motor, and nervous systems of animals. In table 1 we list papers from the last decade that fall within this description (not including the large amounts of work in biologically-based sensory processing except where it is used in behavioral control, i.e. on a robot), demonstrating both the quantity and breadth of current work in this field.

Overview of the Book

This book is an edited collection of papers that were presented at the "Robots and Biology: Developing Connections" American Association for Artificial Intelligence Symposium held on October 23-25, 1998 in Orlando Florida. The purpose of the symposium was to bring together scientists from a diverse array of disciplines all of whom are using biorobots as probes of animal behavior and brain function. The chapters are ordered with those primarily involved with sensory biology presented first, followed by chapters that focus on motor systems, and ending with chapters concerned with higher-level or cognitive processes. This ordering is, of course, artificial because it is difficult if not impossible to cleanly separate functional subsystems within animals. A prime example of this is the use of visual motion for object detection and navigation (Viollet and Franceschini, chapter 4) in which the motor and visual systems are closely coupled to perform this function. Nevertheless, the ordering does serve as a convenient organizational framework for the book and to direct readers with specific interests to specific chapters.

A chapter on neural mechanisms in cricket phonotaxis by Barbara Webb begins the Sensory Systems section. A robot model of a cricket is used to test a neuronal model for sound localization by these noisy insects. Next we dip underwater where Frank Grasso examines the world of olfactory-based guidance in lobsters. The robot presented in Grasso's chapter is one of the first examples of a marine biorobot. Polarized light navigation in insects has long been of interest to biologists and the next chapter by Ralf Möeller and colleagues presents a robot with a visual system modeled after that of the desert ant *Cataglyphis*. "Sahabot" is being used to test hypothesis on how *Cataglyphis* uses the pattern of skylight polarization to find its way back to its desert burrow. This is followed by an invited chapter by Nicolas Franceschini, a pioneer in biorobotics. In this chapter Franceschini and coauthor Stéphane Violett present a novel and robust visual tracking system that utilizes of low amplitude scanning of a photodetector. Such a system may have an analog in the compound the fly in which a tiny muscle oscillates the photoreceptor array.

Two chapters are presented in the Motor System section. In the first, Roger Quinn and Roy Ritzman review their work in developing hexapod robots with cockroach kinematics and control. This work is an excellent example of how the close collaboration of an engineer and a biologist can lead to advances in both fields. The chapter by Holk Cruse presents the intriguing argument that an understanding of how the brain controls complex, multiple degrees of freedom motor systems, such as the six legs of the stick insect, may give us important insight into how the so-called higher cognitive functions are implemented.

The issues addressed in Cruse's chapter lead us into the final pair of chapters on the use of robots to explore higher brain function. Olaf Sporns and Nikolaus Almássy explore the development of perceptual invariance in a neural model patterned after the mammalian inferior temporal cortex. This model was incorporated into a mobile robot with a visual system and was shown to develop pattern-selective "neurons" over time as the robot was permitted to move about within the real world. In the final chapter of this book Brian Scassellati discusses the application of humanoid robots to the study of human social development. The book ends with a discussion of the outstanding issues in biorobotics, given the current state of the art, that were derived from the lively discussions that occurred during the AAAI symposium.

It is our hope that the reader will find these chapters informative and insightful and perhaps inspirational. We do hope, however, that the reader also views these chapters with a critical eye. Biorobotics is an emerging field that will become scientifically strong only through vigorous debate and the application of rigorous standards of scientific utility. It must not be forgotten that a biorobot is a model of a living animal and, like all models, has its appropriate uses and its limits. To aid our readers in the evaluation of work in this field, and to help them develop their own research, we provide the following list of dimensions (Webb 2001) on which biorobotic modeling decisions need to be made:

- *Realism:* whether the model tests and generates hypotheses applicable to biology.
- *Level:* the elemental units of the model in the hierarchy from atoms to societies.
- *Generality:* the range of biological systems the model can represent.
- *Abstraction:* the complexity, relative to the target, or amount of detail included in the model.

Subject area	Examples	References
Simple sensorimotor control		
Chemical	Moth pheromone tracking	Kuwana, Shimoyama, and Miura 1995; Ishida, Kobayashi, Nakamoto, and Moriisumi 1999; Kanzaki 1996; Willis 2000
	Ant trail following	Sharpe and Webb 1998; Russell 1998
	Lobster plume following	Grasso, Consi, Mountain, and Atema 1996; Grasso, Consi, Mountain, and Atema 2000; Ayers et al. 1998
	C. elegans gradient climb	Morse, Ferree, and Lockery 1998
Auditory	Cricket phonotaxis	Webb 1995; Lund, Webb, and Hallam 1998; Webb and Scutt 2000
	Owl sound localisation	Rucci, Edelman, and Wray 1999
	Human localisation	Horiuchi 1997; Huang, Ohnishi, and Sugie 1995
	Bat sonar	Kuc 1997; Peremans, Walker, and Hallam 1998
Visual	Locust looming detection	Blanchard, Verschure, and Rind 1999; Indiveri 1998
	Frog snapping	Arbib and Liaw 1995
	Fly motion detection to control movement	Franceschini, Pichon, and Blanes 1992; Weber, Venkatesh, and Srinivasan 1998; Hoshino, Mura, Morii, Suematsu, and Shimoyama 1998; Huber and Bülthoff 1998; Srinivasan and Venkatesh 1997; Harrison and Koch 1999
	Praying mantis peering	Lewis and Nelson 1998
	Human oculomotor reflex	Horiuchi and Koch 1999; Takanishi, Hirano, and Sato 1998; Shibata and Schaal 1999
	Tracking/Saccade control	Clark 1998; Wagner, Galiana, and Hunter 1994; Schall and Hanes 1998
Other	Ant polarized light compass	Lambrinos et al. 1997, Lambrinos, Möller, Labhart, Pfeifer, and Wehner 2000
	Lobster anemotaxis	Ayers et al. 1998
	Cricket wind escape	Chapman and Webb 1999
	Trace fossils	Prescott and Ibbotson 1997
Complex motor control		
Walking	Stick insect	Cruse et al. 1998, Kindermann et al. 1998, Ferrell 1995; Pfeiffer et al. 1995
	Cockroach	Espenschied et al. 1996,Delcomyn and Nelson 2000, Nelson and Quinn 1998, Binnard 1995
	Four-legged mammal	Ilg et al. 1998, Berkemeier and Desai 1996
Swimming	Tail propulsion	Triantafyllou and Triantafyllou 1995, Kumph 1998
	Pectoral fin	Kato and Inaba 1998
	Undulation	Patel et al. 1998
	Flagellar motion	Mojarrad and Shahinpoor 1997
Flying	Insect wings Bat	Miki and Shimoyami 1998, Fearing 1999, Fearing et al. 2000, Dickinson et al. 1999, Pornsin-Sirirak and Tai 1999
Arms/hands	Spinal circuits	Hannaford et al. 1995;,Williamson 1998
	Cerebellar control	Fagg et al 97, van der Smagt 1998, Hoff and Bekey 1997
	Grasping	Leoni et al. 1998, Hauck et al. 1998
	Haptic exploration	Erkman et al. 1999
Humanoid		Special issue *Advanced Robotics* 116: 1997; Brooks and Stein 1993 Hirai et al. 1998; Yamaguchi and Takanishi 1997
Other	Running and Hopping	Raibert 1986, Pratt and Pratt 1998
	Brachiation	Saito and Fukuda 1996
	Mastication	Takanobu et al. 1998
	Snakes	Hirose 1993, Review in Worst, Miller forthcoming
	Paper wasp nest construct	Honma 1996
Navigation		
Landmarks	Ant/bee landmark homing	Möller 2000; Möller et al. 1998
Maps	Rat hippocampus	Burgess et al. 1997, Gaussier et al. 1997; Recce and Harris 1996
Search	*review*	Gelenbe et al. 1997
Collective behaviours		Beckers et al. 1996; Holland and Melhuish 1999; Melhuish et al. 1998; Kube and Bonabeau 2000
Learning		Edelman et al. 1992; Hallam et al. 1994; Sporns forthcoming, Scutt and Damper 1997, Saksida et al. 1997, Voegtlin and Verschure 1999, Chang and Gaudiano 1998

Table 1: Examples of biorobot research. This is intended to be a representative sampling not a fully comprehensive listing.

- *Accuracy:* how well the model represents the actual mechanisms of behavior.
- *Medium:* the physical basis by which the model is implemented.
- *Performance match:* to what extent the model behavior matches the target behavior.
- *Utility:* the biological understanding, technical insight or communication of ideas that the model provides.

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Note

1. Willis, M. 2000. Modeling Approaches to Understand Odor-Guided Locomotion. This paper is available at http://flightpath.neurobio.arizona.edu/Model/index.html.

Contents

Sensory Systems

CHAPTER

1

A Spiking Neuron Controller for Robot Phonotaxis

Barbara Webb

In their 1988 paper about the auditory behavior of the cricket, Weber and Thorson suggest as a "first model" of phonotaxis:

> "... the simple rule 'turn toward the ear more strongly stimulated.' We use the word simple because a two-eared robot programmed to obey this rule (if suitable noise were incorporated) could be made to track a sound source in a manner like that of the female."

This chapter reports the latest in a series of studies (Webb 1994, 1995; Webb and Hallam 1996; Lund, Webb, and Hallam 1997, 1998) of what is required to make a two-eared robot track sound sources in a manner like the female cricket. In the process many questions have been raised, both about the "simple rules" of phonotaxis, the more general problems of understanding neural control of behavior, and what can be learned from robot models. The ultimate aim in these investigations has been to gain an understanding of how the sensory and neural systems of animals, embedded in appropriate environments, successfully control behavior. A general strategy has been to look for alternatives to the standard "information processing" conception of perception by focusing on how sensors can act as matched filters, how temporal dynamics of neurons can interact, and how environmental conditions control behavior. Consequently the models have the following features:

- As far as possible the models are built as real systems with actual sensors and motors, behaving in the real world. They are also built as whole systems, solving a complete problem of sensorimotor control rather than partial problems of sensing or moving.
- The architectures represent neural processes at appropriate levels of detail rather than using standard artificial neural net abstractions. Individual neuron properties and identified connectivity are included, rather than training methods being applied to generic architectures.

- The systems built are treated as models: the resulting behavior is compared in some detail with biological data, with the aim of assessing how the well the model really explains the observations.

The particular system studied—cricket phonotaxis—is a useful "model" to explore these themes. The behavior is stereotyped, yet nontrivial. The neuroethological understanding of this system is relatively well advanced. Thus an explanation of behavior in terms of neurons should be forth-coming. However, when the rigorous test of trying to build a replica of the system is applied it is quickly evident how far short of a full explanation current research falls. Moreover building the models suggest some alternative plausible explanations.

Cricket Phonotaxis

The female cricket can find a conspecific male by walking or flying towards the calling song the male produces. This sensory cue is sufficient (though not necessary) for finding a mate. Using only auditory cues, the female is able to cover a large distance—ten to twenty meters—negotiating uneven vegetation-covered terrain, and reliably locate a single male, despite other males and other sounds in the vicinity. In the lab the female will track sound for long periods on a treadmill and thus many details of the tracking ability are available (e.g. Thorson, Weber, and Huber 1982; Schmitz, Scharstein, and Wendler 1982; Huber and Thorson 1985; Huber, Moore, and Loher 1989). It is a tractable system for the neuroethological approach, involving a well-defined stimulus and response, an accessible nervous system and a relatively small number of critical neural connections (e.g. Wohlers and Huber 1982; Schildberger 1988; Horseman and Huber 1994; Stumpner , Atkins, and Stout 1995).

Thorson, Weber, and Huber (1982) suggested a basic hypothesis that still underlies most of the research on this system:

> "Once a song is recognized as correct, the female apparently walks towards it by sensing whether the sound source is to the right or left and making suitable corrective turns."

This assumes that recognition of correct songs is an independent, prior event to localization of sound. However, whether a song is recognized is generally assessed by whether the female walks towards it, thus it is possible that failure to approach a song simply indicates failure to make the suitable corrective turns. It has been argued (Weber and Thorson 1988) that the fact that the cricket moves in typical "phonotactic" fashion i.e. stop-start movement with corrective turns, even when sound is played from above and hence contains no useful directional information, is evidence for explicit "recognition," but as will be discussed below this does not necessarily follow.

It is beyond the scope of the current chapter to review the extensive evidence