A Biologically-Based Control System for a Robot Fish

Dr. Martha J. Hiller

January 17, 1994

1 Introduction

Rhythmic motor activity in animals requires the coordination of many different muscles to maintain a quasi-periodic activity pattern with appropriate phase relationships and force and duration of muscle contractions within each cycle. The motor pattern must also be modulated in appropriate ways by sensory feedback and by higher-level control signals defined by the goals of the animal. Sophisticated mechanical systems, including mobile robots as well as many machines used in state-of-the-art factory automation, must solve similar control problems. Biologically-based motor control is therefore a promising approach to the control of these systems.

Much progress has already been made in the design of biologically-motivated systems for robot locomotion. Legged robots are able to use the many degrees of freedom of their limbs to navigate rough and uneven terrain that would be impossible for simpler wheeled autonomous vehicles [1]. A similar situation may hold for underwater locomotion, where a sophisticated vehicle modelled after a fish may be able to move through the water more swiftly and efficiently than a comparable vehicle that uses a traditional propulsion system. Dave Barrett, formerly of the MIT AI Laboratory, is currently working with Prof. Michael Triantafyllou in MIT's Ocean Engineering Department to build such a robot fish. This robot, once built, will require a sophisticated control system to coordinate its movements.

The project I would like to work on next year at ISR is to extend the analysis of the coupled-oscillator model Prof. Avis Cohen, now at the University of Maryland, and others have developed as a result of their study of the neural systems underlying swimming in the lamprey, and use it as a basis for the design of a biologically-motivated intelligent control system for Barrett's robot fish. Similar coupled-oscillator models have already been analyzed for two-legged [2] and six-legged [3] walking, by students working at ISR under Prof. P.S. Krishnaprasad. ISR's commitment to interdisciplinary work and the development of intelligent control systems, and the presence in ISR and at the University of Maryland of researchers working on closely related projects, makes it an ideal place to undertake this work.

2 Project Overview

The project has two major parts. One part involves further modelling and experimentation with aspects of the biological system that are immediately relevant to the controller design. This work would be aimed at extending the analysis of the model in three specific areas: long-range coupling effects, the relationship between intrinsic frequency and phase lags in segmental oscillators, and the effects of lateral line feedback on the brainstem and spinal cord. This work would be done in collaboration with Prof. Cohen and others in her research group in the Zoology Department, and with Prof. Krishnaprasad for the mathematical analysis. Some of this work is already in progress.

The other part of the project is to develop a biologically-motivated control system for the robot fish, inspired by and building on what is known about the lamprey locomotor system. The hardware design lends itself to control by a chain of coupled oscillators, and as the only robot fish currently in existence, it is a valuable resource for testing hypothesized swimming control algorithms under real-world conditions. Although the hydrodynamics of the robot, which is modelled after a tuna fish, are considerably different from those of the lamprey, it is likely that the basic neural control system underlying locomotion in the two animals is quite similar, and that the differences can be compensated for by varying model parameters that control the amplitude and relative timing of bursting in the segmental oscillators and the corresponding contractions in the body.

The robot controller design would be done with Prof. Hendler and Prof. Krishnaprasad at ISR, and tested in collaboration with Dave Barrett and Prof. Triantafyllou at MIT. This would provide an opportunity for the ISR to strengthen its ties with groups doing related research at MIT.

3 Project Description

This section gives details for a preliminary design of the robot controller, and proposes specific modelling and experimental work to further our understanding of aspects of the biological system that are important for the controller design. A more detailed description of related research on the lamprey can be found in Appendix A, and hardware specifications for the robot fish are presented in Appendix B.

3.1 A Preliminary Design for the Controller

The proposed controller design has a number of components, analogous to the known parts of the lamprey locomotor system. A diagram showing the components of the proposed controller is shown in Figure 1. More detailed information about each component follows.

Figure 1: Components of the Robot Fish Controller.

3.1.1 The Segmental Oscillators

The backbone of the controller is a simulated chain of segmental oscillators, ten per body segment. Oscillator output within each segment will be averaged and used to drive the segmental motors. The simulated chain is longer than the number of segments to provide a more continuous underlying system, which will improve the smoothness of movement generation.

Oscillators will be coupled using both short- and long-range connections to improve stability and speed of phase-locking, and ensure a smooth response to proprioceptive feedback. The open-loop amplitudes and phase lags (that is, with coupling, but prior to the introduction of sensory feedback) will be tuned to values that are appropriate for the tuna fish.

3.1.2 Proprioceptive Feedback

Local proprioceptive feedback from “edge cells” will be simulated using motor position and velocity feedback, and will be used to adjust the phase of the oscillators to compensate for mechanical delays in the body’s response to oscillator excitation.

These adjustments will also be used in a learning process to tune the strength of the output connections from oscillators to motors, so that systematic errors will be corrected over time. This will gradually reduce the magnitude of the necessary feedback corrections, so the system operates as far as possible from feedback saturation boundaries.

3.1.3 Higher-level Control from the Brainstem

A descending control signal from a simulated brainstem will be sent to all segmental oscillators. The role of this part of the controller is to control the swimming speed of the robot by adjusting the basic level of oscillator excitation that controls the burst frequency. It therefore receives the desired velocity as an input from the experimenter.

The brainstem also receives feedback from the rostral oscillators to monitor the “spinal” response to its descending control signal, and from the lateral line sensors so that it can respond to environmental information.

3.1.4 Lateral Line Feedback and Swimming Hydrodynamics

Integration of feedback from the lateral line sensors into the neural controller is one of the primary open research areas in the proposed project. Other colleagues of Prof. Triantafyllou are working to understand the hydrodynamics of swimming in the tuna fish. Their results indicate that, as a fish moves through the water, vortices rolling off its lateral fins produce sharp peaks in the water pressure that roll along its body. Swimming speed and efficiency are improved if its tail flip is timed to coincide with the arrival of the vortices at the tail [4].

For efficient swimming, therefore, the time it takes for a pressure vortex to travel from the front fin to the tail should correspond to the time it takes for the travelling wave of muscular contractions to travel the same distance. The pressure sensors along the lateral line of the robot fish can, in theory, be used to detect and respond to these pressure peaks.

By analogy to the lamprey lateral line organ, pressure feedback will be directed to the simulated brainstem to control the swimming burst frequency, and direct local feedback to the segmental oscillators may also be used. These two types of output connections correspond to two different strategies for modulating the timing of the tail flip. Segmental connections can adjust the timing by changing the phase lags between oscillators, while the brainstem acts by changing the burst frequency. The effects of lateral line feedback will be tuned by a learning process to maximize the peak water pressure on sensors near the tail during the tail flip.

Lateral line feedback to the brainstem should allow the fish to accelerate smoothly to swimming at the desired cruising velocity without loss of efficiency, by maintaining the oscillator rhythm at an appropriate frequency for the current swimming speed. Local feedback may also act to fine-tune the response to the descending control signal.

3.2 Related Modelling and Experimental Work

The chain of segmental oscillators in the lamprey spinal cord has been modelled mathematically as a chain of nonlinear phase-coupled oscillators. The equations for the dynamics of the oscillator chain are

$$\dot{\theta}_i = \omega_i + \sum_{j=0}^{N-1} \alpha_{ij}\, H_{ij}(\phi_{ij}) \qquad (1)$$

where θ_i is the phase of the ith oscillator in an N-oscillator chain, ω_i is its intrinsic frequency, α_{ij} is the coupling strength from oscillator j to oscillator i and H_{ij} is the corresponding coupling function, giving the phase dependence of the connection, and $\phi_{ij} = \theta_j - \theta_i$ is the phase lag from node j to node i.

Much of the modelling work with coupled oscillators makes a number of simplifying assumptions, such as including coupling only between nearest neighbors, and using uniform coupling strengths and uniform intrinsic frequencies along the cord. More recent models have focussed on the effects of relaxing some of these assumptions, but much work remains to be done in this area. The research proposed below relates to three specific aspects of the model: long-range coupling effects, the relationship between intrinsic frequency and phase lags in segmental oscillators, and the effects of lateral line feedback on the brainstem and spinal cord.

3.2.1 Long-range Coupling

Long-range coupling is important for increasing the stability and smoothness of movements, and for attaining fast phase-locking between oscillators on system startup. Although some work has been done in this area, much is still unknown. The work suggested here is for a restricted class of coupling equations that are compatible with what is known about coupling in the lamprey and are amenable to mathematical analysis. These coupling equations are of the form

$$\alpha_{ij} = F(x_{ij}) = \begin{cases} \sum_{k-} a_{k-}\ e^{x_{ij}/\lambda_{k-}} & \text{when } j < i \\ \sum_{k+} a_{k+}\ e^{-x_{ij}/\lambda_{k+}} & \text{when } i < j \end{cases} \tag{2}$$

$$H_{ij}(\phi_{ij}) = \phi_{ij} - \Phi(x_{ij}) \tag{3}$$

where $x_{ij} = j - i$ is the distance from oscillator j to oscillator i, $k-$ subscripts a set of amplitudes and length constants for descending coupling, and $k+$ subscripts a set of amplitudes and length constants for ascending coupling. $\Phi(x_{ij})$ is the target phase shift of connections at distance x_{ij}, and can take a variety of forms. The equation for the long-range coupling strength is based on recent results by Buchanan [5], which indicate that the number of neurons in a spinal cord segment that are directly connected to neurons in another segment falls off exponentially with the distance between the segments. His data also indicates the presence of two sets of coupling connections with different length constants.

Use of a linear function for the phase response matches data shown in the first lamprey modelling paper [6], as long as the magnitude of the phase difference is less than 50% of a cycle.

I have recently shown that long-range coupling equations of this form can be approximated by a nearest-neighbor model if we assume an approximately uniform phase lag, so that $\phi_{ij} \approx x_{ij}\ \phi_{i(i+1)}$, and set $\Phi(x_{ij}) = x_{ij}\Phi$, where Φ is a constant. The coupling function for descending coupling is

$$\sum_{j=0}^{i-1} \alpha_{ij}\ H_{ij} \approx \sum_{j=0}^{i-1} F(x_{ij})\ x_{ij}\ (\phi_{i(i+1)} - \Phi) \tag{4}$$

We can further approximate by replacing the discrete sum with an integral, to arrive at an analogous nearest-neighbor coupling function with a coupling strength and phase dependence of

$$\alpha'_{i(i-1)} = \int_0^i F(x)\ x\ dx \tag{5}$$

$$= \int_0^i \sum_{k-} a_{k-}\ e^{x/\lambda_{k-}}\ x\ dx \tag{6}$$

$$H'_{i(i-1)}(\phi_{i(i-1)}) = \phi_{i(i-1)} + \Phi \tag{7}$$

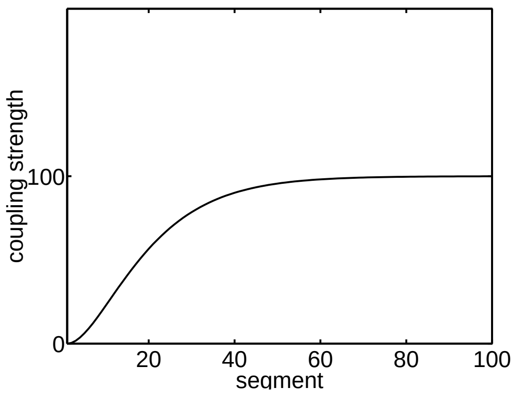


Figure 2: Analogous nearest-neighbor coupling strength $\alpha'_{i(i-1)}$ for descending coupling, for the length function $F(x_{ij}) = e^{x_{ij}/10}$ and the coupling function $H_{ij}(\phi_{ij}) = \phi_{ij} + x_{ij}\ \Phi$.

for an oscillator i segments from the rostral end of the cord. If there is a single descending length constant, λ, with amplitude $\alpha = 1$, the descending coupling strength is of the form

$$\alpha'_{i(i-1)} = \lambda^2\ (1 - e^{-i/\lambda}(1 + i/\lambda)) \tag{8}$$

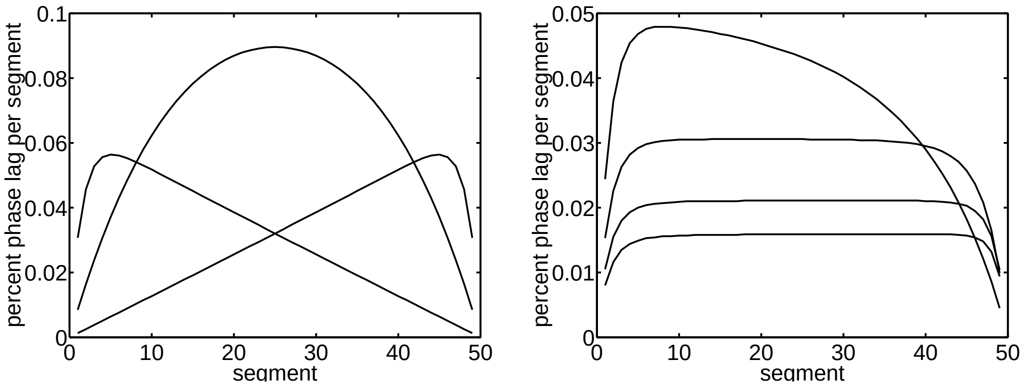
A graph of this function for $\lambda = 10$ is shown in Figure 3.2.1.

The existence of an analogous nearest-neighbor model greatly simplifies the analysis of this class of coupling equations, and work is currently underway to extend the analysis of nearest-neighbor models to cases where the coupling strength is non-uniform.

3.2.2 Relationship Between Frequency and Phase

The relationship between the intrinsic frequency of the segmental oscillators and the phase lags between them is a very active area of research. Some models of intersegmental coupling assume that the phase lags are determined by phase shifts in the coupling functions, and that differences in the intrinsic frequency are merely a problem to be overcome. Other models use intrinsic frequency differences or gradients to produce the phase lag. The primary problem for both sets of models is how to explain the uniformity of phase lags along the chain in the presence of experimentally observed differences in intrinsic frequency at the rostral and caudal ends of the cord. An answer to this question will also lend further insight into the effects of more local perturbations in intrinsic frequency such as might be produced by sensory feedback.

The non-uniform coupling strength implied by my analysis of long-range coupling suggests a form of the nearest-neighbor coupling equation that has not previously



(a) (b)

Figure 3: An example of the phase lags seen along the cord in simulations of coupled-oscillator models in the presence of a gradient in intrinsic frequency, e.g., $\omega_i = \Omega + i\,\epsilon$. A roughly uniform phase lag is seen in experimental preparations. a) samples of the non-uniform phase lags seen using a uniform coupling strength. b) samples of phase lags seen with a gradient in descending coupling strength. The phase lags are uniform for suitable choices of coupling strength parameters, except for a boundary layer at each end of the cord.

been analyzed. Preliminary results using coupling equations with a linear gradient in coupling strength show that they are able to produce uniform phase lags in the presence of an intrinsic frequency gradient, unlike other nearest-neighbor coupling equations currently in use. An example is shown in Figure 3.2.2.

Serotonin, a neuromodulator that is endogenous to the lamprey spinal cord, has been shown to differentially affect the rostral and caudal ends of the cord, which both changes the steepness of the intrinsic frequency gradient and increases the phase lags. This property can be used to further study the relationship between phase lags and systematic differences in intrinsic frequency along the cord. Suzanne Dykstra, a graduate student in Prof. Cohen's group, is currently working on a set of experiments to determine the effects of serotonin on intersegmental coupling, which will be used to supplement this part of the analysis.

3.2.3 Lateral Line Feedback

Information about the possible role of lateral line feedback suggest another set of experiments to be done in the lamprey. Initial plans are to experiment with animals where a flap of skin is left intact along the lateral line during dissection, and use a water jet to stimulate lateral line sensors. Recordings would be taken from both brainstem and spinal cord to determine the effects of this stimulation.

4 Summary

Several different lines of research come together in this project to produce a highly sophisticated control system for a robot fish. Experimental work in neuroscience provides the basic design for the controller, and ongoing experimental work is producing more detailed information about the biological control system. Mathematical analysis of phase-coupled oscillator models improves our understanding of the dynamic behavior of such systems and of their underlying structure. Hydrodynamics research suggests a possible functional role for one type of sensory feedback. And the robot hardware provides a valuable opportunity to test the control system under real-world operating conditions.

A The Lamprey

A.1 The Lamprey Locomotor System

The lamprey has approximately 100 spinal cord segments. A pair of oscillating central pattern generators is present in each segment, which generate the neural control signals to produce "fictive swimming" in the experimental preparation. During swimming, these oscillators are coordinated through both short- and long-range coupling to produce a sinusoidal travelling wave of contractions along the body, such that at any point in time there is one full period of the waveform along the length of the body. The time lag between bursts of activity in neighboring segments is therefore inversely proportional to the burst frequency, and the phase difference is maintained at approximately 1% per segment, regardless of swimming speed. The activity of the left and right sides of the animal are constrained to be 180° out of phase by mutually inhibitory cross-coupling, so that each oscillator pair can be modelled as a single segmental oscillator which alternately drives the left and right sides of the animal.

A.2 Coupled-Oscillator Models

Equation 1 is a general equation governing the dynamics for one-dimensional chains of phase-coupled oscillators.

This equation can be made to produce behavior similar to that of the lamprey by setting the intrinsic frequencies constant, using nearest-neighbor coupling with uniform coupling strengths for ascending and descending coupling, and using a phase-shifted coupling function:

$$\omega_i = \Omega \tag{9}$$

$$\alpha_{ij} = \begin{cases} \alpha_u & \text{when } j = i+1 \\ \alpha_d & \text{when } j = i-1 \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

$$H_{ij}(\phi_{ij}) \;=\; H(\phi_{ij} - \Phi) \tag{11}$$

where $H()$ is an odd function and $\Phi = 0.01$ is the target phase shift.

Most of the early modelling work with coupled oscillators was simplified by assuming equations of this or a similar form. However, certain aspects of the biological system are known not to conform to these constraints, and more recent models have focussed on the effects of relaxing some of these simplifying assumptions.

A.3 Long-range Coupling

It has been known for some time that long-range coupling is present in the lamprey, but the nature of this coupling is only now being explored. Tim Kiemel [7] tested the effects of long-range coupling to a single distant node in computer simulation. Long-range coupling has two primary benefits: it increases the stability of the system under noisy conditions [8], and phase-locking occurs more quickly after startup [9][1]. The smoothing effect of receiving inputs from several neighbors may also affect the system's response to local sensory feedback, by distributing the effects of the resulting non-uniformity in excitation over a larger number of segments.

Analyzing the effects of long-range coupling, however, can be quite difficult. A restricted class of models with multiple short-range connections have been analyzed and found to behave in a similar manner to nearest-neighbor coupling [11], but in general the effects of longer-range coupling connections are not well understood. Extending this analysis to encompass a broader class of long-range coupling patterns is an ongoing area of research.

A.4 Non-uniform Intrinsic Frequencies

The intrinsic frequencies of the oscillators can be affected in many different ways. Consistent differences in intrinsic frequency along the cord may be caused by differences in coupling strength or other properties intrinsic to the oscillators. Short-term modulation of oscillator frequencies may be produced by descending control signals from the brainstem, sensory feedback, or the presence of neuromodulators such as serotonin.

Understanding the role of descending control and of sensory feedback is clearly crucial to the design of a control system based on a coupled-oscillator model. Certain aspects of this problem have already been studied, but much work remains to be done in this area.

A.4.1 Proprioceptive Feedback

Sensory feedback from edge cells, which respond to mechanical stretch and produce local changes in the excitation of nearby oscillators, has been studied using forcing

[1] But see [10], where the same result is achieved without the use of long-range coupling.

experiments, where one end of the cord is mechanically driven at a known frequency. Under appropriate experimental conditions, the frequency of the entire cord can be entrained to match the frequency of the forcing signal. This technique has also been used to test for hypothesized asymmetries in the properties of ascending and descending coupling [12].

A.4.2 The Brainstem

Recent work in Cohen's lab [13] gives experimental evidence for slow periodic bursts of activity in control neurons in the brainstem that give rise to swimming activity. Descending outputs from the brainstem run the entire length of the spine, while ascending feedback is received primarily from the rostral end. A project is currently underway to model the effects of this descending control signal.

A preliminary analysis of the brainstem data indicates that its effect on the swimming rhythm depends on the burst frequency of the oscillator rhythm [14]. This may indicate a role in compensating for differences in hydrodynamic properties at different swimming speeds.

A.4.3 The Lateral Line Organ

Lateral line feedback has not been extensively studied in the lamprey. A lateral line organ is present which sends its primary output to the brainstem [14], but which may have direct local connections as well. Its function in the lamprey is not known, though the efficiency of lamprey swimming is known to be quite high, which may indicate the use of a strategy similar to that hypothesized for the tuna fish.

A.4.4 Neuromodulator Effects

The effects of serotonin, a neuromodulator that differentially affects intrinsic frequencies in the rostral and caudal ends of the cord, are also currently being studied. This neuromodulator slows and intensifies the oscillator rhythm, acting preferentially on the caudal end of the animal, and increases phase lags between oscillators. Serotonin can be used to study changes in oscillator coordination that result from a gradient in intrinsic frequency along the cord.

The purpose of serotonin is unknown, although one can speculate that it may be useful for swimming under different hydrodynamic conditions, or for the generation of docking or other, slower rhythmic behaviors. The control needs of the robot fish may eventually suggest a role for serotonin.

B The Robot Fish

The robot described in this appendix was designed by Dave Barrett in the Ocean Engineering Department at MIT. The hardware is currently under construction and should be ready to go in the water later this spring. A prototype has already been built. Schematics of the robot hardware are attached at the end of this proposal.

B.1 Robot Hardware

B.1.1 Mechanical Structure

The robot's overall shape is modelled after a tuna fish, which has a relatively rigid front section and a freely-moving tail that provides the force for its forward motion during swimming (see attached figures.) The robot has six body segments and a nose cone; each joint is free to move in a plane parallel to the water surface.

B.1.2 Motors and Motor Feedback

The joints are controlled by 6 brushless DC servo motors located on a sled which runs on a track above the wave tank. The joints are connected to the motors by a set of tendons that runs through a hollow mast. The motors provide position, velocity, acceleration, and jerk feedback, and there are 12 additional force sensors on the tendons, one on the left and one on the right for each joint.

B.1.3 Lateral Line Sensors

The robot has a reticulated foam covering with an elastomeric skin, wrapped around a set of "ribs" that give it its overall shape. The surface of the skin is outfitted with 200 pressure sensors, 100 on each side, to detect water pressure along the lateral line of the body. The pressure sensors output a voltage proportional to the water pressure.

B.1.4 Computational Hardware

Electronics for the sensors are contained in a fiberglass nosecone. A PC, with control software written in C, is contained in the sled along with the motors and servo system. The sensors are continuously scanned and their values are updated over a high-speed data bus and stored in registers in the PC.

B.2 Efficiency Measurements

There is one additional force sensor on the mast, which is used to measure the power output of the robot fish as it moves through the water. During testing, the sled is constrained to move at a constant velocity, and the robot swims to keep up with it. The force on the mast is determined by the difference between the robot's swimming speed and the speed of the sled. The power used by the robot is determined by the tendon forces and velocities.

$$
\begin{aligned}
P_{out} &= F_{mast} \times v_{sled} \\
P_{in} &= \sum_{i \in tendons} F_i \times v_i
\end{aligned}
$$

An alternate method of measuring efficiency would be to use the force sensing on the mast in a separate sled controller, and match the speed of the sled to the speed of the fish. The corresponding efficiency measurements would be the power input required to accelerate to and maintain a given swimming velocity. This would allow testing of acceleration and deceleration as well as swimming performance at constant velocity.

Another design goal for the controller is to produce smooth movements with minimal jerk on the motors. This can be measured directly from motor feedback signals.

B.3 Software Controller

The robot is currently being controlled by a simple closed-loop PID controller, for demonstration purposes. The controller moves the body with a sinusoidal travelling wave that travels along the body at 80% of the desired swimming velocity.

The final controller for the fish, if it is to realize its full potential as a fast and efficient swimmer, will clearly need to be far more complex than the current design. However, actual work on upgrading the controller is still in the earliest pre-planning stages. It is hoped that the controller design proposed here will provide the robot with a sophisticated and adaptive solution to the requirements of fast and efficient locomotion in its underwater environment.

References

[1] R. A. Brooks, 1989, "A Robot that Walks; Emergent Behavior from a Carefully Evolved Network", Neural Computation 1:2,253–262.

[2] S. Mishra, 1993, "Control of biped locomotion using oscillators", ISR Thesis Report M.S. 93–12, University of Maryland.

[3] D. J. Marvin, 1992, "Coordination of the walking stick insect using a system of nonlinear coupled oscillators", ISR Thesis Report M.S. 92–9, University of Maryland.

[4] L. Rome, D. Swank, and D. Coorda, 1993, "How Fish Power Swimming", Science 261:16.

[5] J. Buchanan, unpublished results.

[6] A. H. Cohen, P. J. Holmes, and R. H. Rand, 1982, The nature of the coupling between segmental oscillators of the lamprey spinal generator for locomotion: A mathematical model. J Math Biol 13:345–369.

[7] T. Kiemel, 1990, "Three problems from the mathematics of neural oscillations", Ph.D. Thesis, Cornell University.

[8] A. H. Cohen and T. Kiemel, 1993, "Intersegmental coordination: lessons from modeling systems of coupled non-linear oscillators", American Zoologist 33:54-65.

[9] D. M. Kammen, P. J. Holmes, and C. Koch, 1989, "Cortical architecture and oscillations in neural networks: Feed-back versus local coupling", In: R. J. M. Cotterill (ed), *Models of brain function*, Cambridge University Press, Cambridge, 273-284.

[10] D. Somers and N. Kopell, 1993, "Rapid synchronization through fast threshold modulation", Biol Cybern 68:393-407.

[11] N. Kopell and W. Zhang and G. B. Ermentrout, 1990, "Multiple coupling in chains of oscillators", SIAM J Math Anal 21(4):935-953.

[12] T. L. Williams, K. A. Sigvardt, N. Kopell, G. B. Ermentrout and M. P. Remler, 1990, "Forcing of coupled nonlinear oscillators: studies of intersegmental coordination in the lamprey locomotor central pattern generator", J Neurophysiol 64:862.

[13] A. H. Cohen, L. Guan and J. C. Harris, 1993, "Interactions between brainstem and central pattern generator for locomotion in adult lamprey", Society For Neuroscience Abstracts, 348.

[14] A. H. Cohen, personal communication.