PAPER

A Conserved Neural Circuit-Based Architecture for Ambulatory and Undulatory Biomimetic Robots

AUTHORS
Joseph Ayers
Anthony Westphal
Daniel Blustein
Department of Biology and
Marine Science Center,
Northeastern University

ABSTRACT

The adaptive capabilities of underwater organisms result from layered exteroceptive reflexes responding to gravity, impediment, and hydrodynamic and optical flow. In combination with taxic responses to point sources of sound or chemicals, these reflexes allow reactive autonomy in the most challenging of environments. We are developing a new generation of lobster and lamprey-based robots that operate under control by synaptic networks rather than algorithms. The networks, based on the command neuron, coordinating neuron, and central pattern generator architecture, code sensor input as labeled lines and activate shape memory alloy-based artificial muscles through a simple interface that couples excitation to contraction. We have completed the lamprey-based robot and are adapting this sensor, board, and actuator architecture to a new generation of the lobster-based robot. The networks are constructed from discrete time map-based neurons and synapses and are instantiated on the digital signal processing chip. A sensor board integrates inputs from a short baseline sonar array (for beacon tracking and supervisory control), accelerometer, a compass, antennae, and optionally chemosensors. Actuator control is mediated by pulse-width duty cycle coding generated by the electronic motor neurons and a comparator and power field-effect transistor (FET) system housed on low- and high-current driver boards. These circular boards are stacked in a tubular hull with the processor and batteries. This system can readily mimic the biomechanics of the model organisms by the addition of hydrodynamic control surfaces. The behavioral set results from chaining sequences of exteroceptive reflexes released by sensory feedback from the environment.

Keywords: biomimetic, robot, UUV, lobster, lamprey

Introduction

The innate behavior of underwater animals provides an effective model for the adaptive behavior of unmanned underwater vehicles (Ayers, 2004). Underwater animals must respond to a broad variety of environmental challenges including turbidity, hydrodynamic flow, heterogeneous and highly structured bottom types and impediment. Their relatively neutral buoyancy renders them especially susceptible to hydrodynamic perturbation. As a result, they have evolved a behavioral set that includes a broad variety of compensatory responses to perturbation. This behavioral set results from layered exteroceptive reflexes responding to exteroceptive sensor input resulting from changes in orientation relative to gravity, impediment, chemical cues, and hydrodynamic and optical flow (Ayers, 2004; Blustein & Ayers, 2010). These layered exteroceptive reflexes can form taxic responses to point sources of sound or chemicals (Westphal et al., 2011). As the point sources form motivational cues for goal achieving behavioral sequences, they can guide reactive autonomy in the most challenging of environments. The task is to capture these performance advantages in engineered devices.

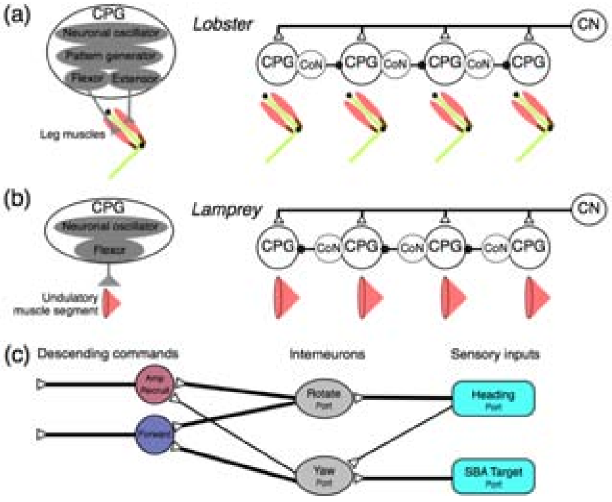
The Biological Model

We are developing a new generation of lobster and lamprey-based robots that operate under control by synaptic networks rather than algorithms. Previous generations of these vehicles were controlled by finite state machines that were organized around the elements of the corresponding neurobiological models (Ayers et al., 2000; Ayers & Witting, 2007).

The neuronal circuits that control our current generation of vehicles are based on the command neuron, coordinating neuron, central pattern generator (CCCPG) architecture (Figures 1a and 1b) of innate animal behavior (Kennedy & Davis, 1977; Stein, 1978; Pearson, 1993). The networks are organized into segmental central pattern generators (CPGs) that control appendages or axial body musculature in the

FIGURE 1

CCCPG architecture with exteroceptive reflex. Labeled circles represent neurons; synapses are shown as connecting lines with triangular (excitatory) or circular (inhibitory) endpoints. (a) Neuronal circuit-based controller for a walking lobster robot. The effector organs of each body segment are controlled by CPGs that contain a neuronal oscillator, a pattern generator and sets of motor neuron pools. The CPGs are coordinated among themselves by a set of coordinating neurons (CoN) that provide information about the activity status of a governing oscillator to a governed oscillator. The CPGs are brought into operation by a set of command neurons (CN) that initiates their operation and controls their average frequency and amplitude. (b) Neuronal circuit-based controller for a swimming lamprey robot. Slight modification of the CCCPG architecture and effectors transforms the system's motor output from walking to swimming. (c) The CNs are organized into exteroceptive reflexes that are released by neuronally coded sensor information (rounded rectangles: heading from a compass, target orientation from SBA) through sensory interneurons, which mediate in place rotation and yaw during locomotion.



animal models and the robots (Ayers et al., 2010). The CPGs are coordinated among themselves by a category of neurons called coordinating neurons that pass status information from a governing CPG to a governed CPG that alters its period to remain coordinated at a particular phase, depending on the ratio of intrinsic frequencies of the governing and governed CPGs (Selverston & Ayers, 2006). This temporal resetting occurs on a cycle-by-cycle basis to entrain the CPGs in a particular gait in the case of walking or to ensure propagation of a wave of flexion down the body during undulation (Figure 1).

The CPGs are brought into operation and modulated by a category of neurons called command neurons (Kupfermann & Weiss, 1978). Command neurons generally constitute the locus at which the decision to evoke a behavioral act is made and project from the brain through the central nervous system to bring the segmental CPGs into operation. They typically perform this process through the mechanism of neuromodulation through second messengers that alter both the cellular properties and synaptic connectivity within the CPG (Dickinson, 2006). By this mechanism or through direct synaptic modulation, the same CPG can often produce variations on a behavioral act in response to different commands (Selverston & Ayers, 2006).

The sensors we employ are configured to encode sensory input as a labeled line code (Bullock, 1968). In this form of coding, each sensory neuron is a unique source of information. The information consists of (1) the nature of the sensory stimulus (light, optical flow, chemicals, bumps, etc.), (2) the receptive field or position of the stimulus on the body and (3) the magnitude of the stimulus coded as an action potential train where the frequency of the action potentials is proportional to the logarithm of the stimulus intensity. We configure these sensory elements in networks that filter out features of the environment through lateral inhibition, range fractionation and motion detection. These filtered outputs provide input to the command neurons to release behavior.

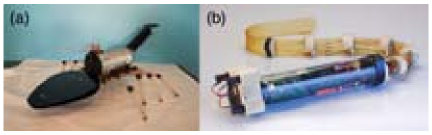
We have completed the lamprey-based robot and are adapting this sensor, board, and actuator architecture to a new generation of the lobster-based robot (Figure 2). The lamprey robot features an electronic nervous system that we are adapting to the new lobster-based robot. The key feature of this architecture is that it is generalizable between all animal models.

Electronic Nervous Systems

The discrete time map-based (DTM) neuron and synapse equations (Rulkov, 2002) phenomenologically model neuronal activity. The model has two state variables x and y, two

FIGURE 2

Biomimetic robots. (a) Fourth generation lobster-based robot. (b) Second generation lamprey-based robot.



control parameters α and σ, and a parameter β for integrated synaptic input. Variations in α and σ can configure neurons into a silent type, a spiking type, a bursting type and a chaotic type (Ayers & Rulkov, 2007). Similar control parameters for the synapse instruments determine the synaptic strength, relaxation rate, release threshold, and reversal potential that determine whether the synapse is excitatory or inhibitory. The electronic nervous systems are first prototyped in the National Instruments LabVIEW™ software. Neuron and synapse instruments are configured with different properties, and the modeled neurons and synapses are wired together in LabVIEW™.

Figure 3 demonstrates a simple CPG circuit configured to illustrate operation of the four types of neurons in our CPGs. Here, a command neuron (1) initiates an oscillation between a bursting neuron (2) and a spiking follower (3) using a slow modulatory synapse. A fourth coordinating neuron (4) can be activated in bursts to entrain the bursting pattern evoked by the command. In contrast to coordinating neurons that reset the timing of the oscillation on a cycle-by-cycle basis by perturbation, command neurons initiate operation of the circuits and modulate their average frequency and amplitude as parameters (Figure 3b–c).

Board Architecture

The networks that control the robots are constructed from DTM neurons and synapses in procedural C and are instantiated on a Texas Instruments digital signal processing (DSP) chip. A common board architecture is used to control both the swimming and walking robots (Figure 4a). The board set consists of four types:

FIGURE 3

DTM network integration. (a) The modeled neuronal circuit: (1) command neuron, (2) bursting neuron, (3) spiking neuron, (4) coordinating neuron. (b) Parametric modulation of 2 and 3 generates an antagonistic bursting pattern. Voltage vs. simulation iteration traces are shown for each component of the network. The trace below neuron 1 shows the current injected to initiate activity. (c) Perturbation of the bursting pattern in 2 by a coordinating neuron (3) to entrain the evoked rhythm. The trace below 4 shows the injected current into that neuron. Adapted from Ayers and Rulkov (2007).

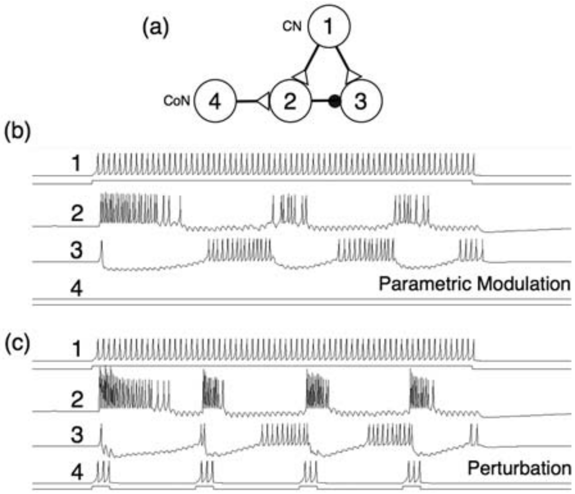
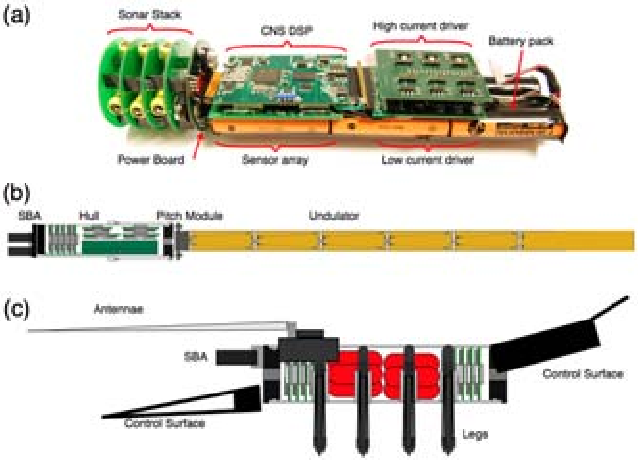


FIGURE 4

Configuration of robots. (a) Current implementation of board set of the lamprey-based robot. The *sonar stack* processes the analog hydrophone signals from the short baseline array (SBA). The electronic nervous system is instantiated on a Texas Instruments TMS320C6727 chip on the *CNS* DSP board. Sensors and the SBA processor are housed on the sensor array board. *Low-* and *high-current drivers* provide the current pulse trains that activate the nitinol actuators. The robot operates on a 12-V, 4.5-Ah NiMH battery pack. (b) Configuration of the lamprey robot. A hinge in the *pitch module* allows the *undulator* to alter its pitch relative to the *hull* to dive or climb. (c) Configuration of the lobster robot. A tubular hull similar to the lamprey robot houses the electronics and batteries. Anterior claw-like and posterior abdomen-like hydrodynamic control surfaces provide a thrust vector into the substrate to increase traction. Externally mounted sensors include optical flow detectors, hydrodynamic flow sensors on the antennae, and sonar transducers for beacon tracking and supervisory input.



(1) The DSP board houses the DSP chip and interconnects to sensor and actuator boards. (2) A sensor array houses a compass, inclinometers, accelerometers and a processor board to derive azimuth and inclination deviation signals from the short baseline array stack. (3) A low-current driver board receives logic signals from the motor neuron output from the DSP chip and in turn controls (4) a high-current driver that applies current to heat the individual nitinol actuators.

Artificial muscles constructed from the shape memory alloy nitinol move both the walking legs and the undulatory body axis. The nitinol is operated on a thermal cycle. When cooled by seawater, it can be deformed into martensite state that is associated with about a 5% length increase. When heated by electrical current, it transforms into the austenite state and contracts rapidly. Increases in the length of one muscle are produced by the contraction of its antagonist. Both the amplitude and velocity of the contractions can be graded by pulse-width duty cycle modulation of the drive pulses. Excitation-contraction coupling with the motor neurons is mediated by a comparator circuit on the low current boards that thresholds the action potentials to generate a square wave pulse that controls a power on the high-current boards to activate the actuators. Changes in the firing frequency of the motor neurons provide the duty cycle modulation.

A common DSP board (Figure 4a) interfaces the sensor array board to the current driver boards. A separate regulator board provides the load to these boards via a 12 V NiMh battery pack. Feed-through connectors in the end caps lead the current conductors to the actuators. The boards are stacked in a tubular hull whose length can be varied to accommodate a variety of mission packages.

Behavioral Set

This system can readily mimic the biomechanics of the model organisms by the addition of hydrodynamic control surfaces. Turns in the undulatory robot are mediated by modulation of the amplitude of the flexions to the two sides as in the animal model (Ayers, 1989). The direction of propagation of the flexion waves along the body axis can be reversed to mediate backward swimming. Dives and climbs can be mediated by alteration of the pitch of the hull relative to the undulator (Figure 4b). Dorsal flexion of the hull generates a low-pressure area above the hull to mediate a climb while ventral flexion generates a low-pressure area below the hull to mediate diving.

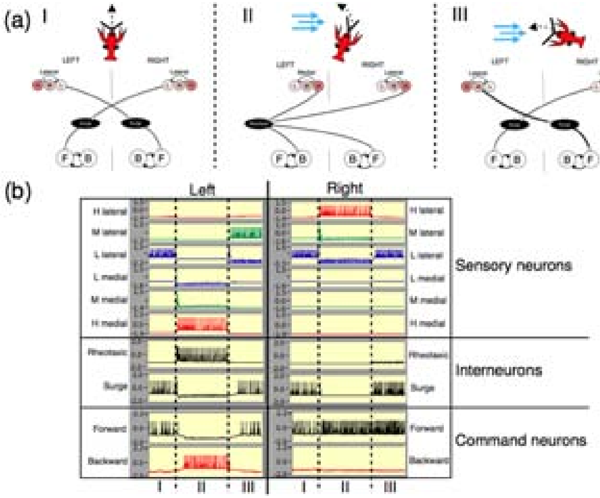
The primary response to hydrodynamic flow in the lobster is to orient into the flow, lower the anterior control surfaces and elevate the posterior control surfaces. As the lobster is only slightly negatively buoyant, this creates a thrust vector into the substrate and increases the traction of the legs on the bottom. The three degree of freedom walking legs of the lobster robot allow the vehicle to walk in all directions (Ayers & Witting, 2007). Alterations in the degree of depression can regulate the height above the substrate, while variations along the long body axis regulates pitch. Biasing the depression on the two sides can correspondingly regulate roll to maintain primary orientation on tilted substrates.

The behavioral set of both robots is organized around exteroceptive reflexes (Kennedy & Davis, 1977). An innate releasing mechanism composed of sensory neurons and interneurons filters incoming information to extract relevant features of the environment such as bumps, tilt, hydrodynamic and optical flow (Figures 1c and 5a). These sensory releasers are coded in interneurons that, in turn, activate command systems. The interneurons use lateral inhibition from low-threshold to high-threshold elements to produce range fractionation so that different ranges of a scalar input are coded by different sensory neurons, providing the capability for detailed circuit logic.

An example of such exteroceptive reflexes are those involved in the mediation of the yaw plane responses to hydrodynamic flow that occur during rheotaxis. Lobsters typically walk with their antenna projected to the front (Figure 5a, I). If wave surge occurs from the side, it bends the upstream antenna medially and the downstream antenna laterally (Figure 5a, II). Our hypothesis is that this perturbation activates a rheotaxic interneuron that activates the backward walking command on the upstream side and the forward walking command on the downstream side. This would cause the animal/vehicle to rotate in place into the flow. While orienting into flow, the animals project their antenna laterally, which would switch control to another bilateral pair of surge interneurons (Figure 5a, III). As the most upstream antennae would be bent more than the more downstream antenna, and these interneurons project to the contralateral forward walking commands, the animal/vehicle would continue to yaw into the flow until current to the two antenna is balanced ensuring proper orientation into the flow for maximal hydrodynamic stability. The hydrodynamic control surfaces can then ensure proper traction to overcome the perturbation.

FIGURE 5

Neural simulation of rheotaxis. (a) Epochs of a lobster's rheotaxic behavioral response to water surge shown with the predominant active neural reflex circuit. In the network diagrams, top circles represent sensory neurons corresponding to *high* (H), *medium* (M), or *low* (L) antennal bending in the *lateral* or *medial* direction. Black ovals represent interneurons that project to bilateral commands for *forward* (F) or *backward* (B) walking. In I, as a lobster walks forward, bilaterally balanced low lateral bending of the antennae is observed, which serves to sustain forward locomotion. In II, left-to-right water surge (blue arrows) causes a high medial bend of the ipsilateral antenna and a high lateral bend of the contralateral antenna eliciting rheotaxis. In III, bilaterally asymmetrical lateral antennal bending mediates yawing upstream during forward walking. (b) Voltage vs. time traces for the neurons of the rheotaxis circuit. Dashed lines distinguish the behavioral epochs shown in a.



This overall control scheme applies to a variety of environmental circumstances and perturbations in the yaw, pitch, and roll planes. Many exteroceptive reflexes form taxic systems. For example, the three hydrophone short baseline sonar array (SBA) on the lamprey robot reports the deviation of the sonar beacon relative to the hull orientation in terms of inclination and azimuth (Westphal et al., 2011). The azimuthal signal modulates swim command systems to cause the vehicle to yaw toward the beacon (Figure 1c) while the inclination signal modulates the pitch system to cause the vehicle to climb/dive toward the beacon. Taken together these layered reflexes will cause the vehicle to home on a sonar beacon. A similar 2-D SBA is planned for the lobster robot to control yaw taxis.

The sonar transducers also provide a capability for supervisory control. The vehicles will be sent supervisory commands that specify a heading and odometry information for distance. The command will include a propensity to negotiate or investigate obstacles depending on the mission. At the end of the search vector, the vehicle would annunciate its location to a long baseline sonar array and be sent a new search vector. By this mechanism an operator could supervise several robots simultaneously.

Conclusion

The neuronal mechanisms of innate behavior can be applied to a broad variety of biomimetic underwater robots. Minimal modification of neuronal components can easily alter locomotory outputs of a network, as we have shown to produce both swimming and walking. Even hybrid systems can be achieved, such as the gait of an alligator resulting from a combination of the lamprey and lobster CPG networks. Sensor packages can be adapted with little restructuring. Layered exteroceptive reflex networks provide capabilities for navigation, investigation and obstacle negotiation in unpredictable near-shore marine environments with a minimum of supervisory control.

Lead Author:

Joseph Ayers
Department of Biology and
Marine Science Center
Northeastern University,
East Point, Nahant MA 01908
Email: lobster@neu.edu

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