

Controlling a lamprey-based robot with an electronic nervous system

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Abstract. We are developing a biomimetic robot based on the Sea Lamprey. The robot consists of a cylindrical electronics bay propelled by an undulatory body axis. Shape memory alloy (SMA) actuators generate propagating flexion waves in five undulatory segments of a polyurethane strip. The behavior of the robot is controlled by an electronic nervous system (ENS) composed of networks of discrete-time map-based neurons and synapses that execute on a digital signal processing chip. Motor neuron action potentials gate power transistors that apply current to the SMA actuators. The ENS consists of a set of segmental central pattern generators (CPGs), modulated by layered command and coordinating neuron networks, that integrate input from exteroceptive sensors including a compass, accelerometers, inclinometers and a short baseline sonar array (SBA). The CPGs instantiate the 3-element hemi-segmental network model established from physiological studies. Anterior and posterior propagating pathways between CPGs mediate intersegmental coordination to generate flexion waves for forward and backward swimming. The command network mediates layered exteroceptive reflexes for homing, primary orientation, and impediment compensation. The SBA allows homing on a sonar beacon by indicating deviations in azimuth and inclination. Inclinometers actuate a bending segment between the hull and undulator to allow climb and dive. Accelerometers can distinguish collisions from impediment to allow compensatory reflexes. Modulatory commands mediate speed control and turning. A SBA communications interface is being developed to allow supervised reactive autonomy.

Keywords: central pattern generator; biomimetic; autonomy; electronic neurons; robotics.

1. Introduction

The ability of even simple invertebrates to outperform the mobility of the most sophisticated robots has suggested a biomimetic approach to the problem of how to achieve truly autonomous robotic devices (Ayers *et al.* 2002, Taubes 2000). The quest to couple sensing devices with motor control led to behavior-based algorithmic control architectures in the 1980's (Brooks 1991). The use of motors to control these early systems, however, necessitated the use of electronic interfaces that differ profoundly from the control principles used by animals. For example, animals grade muscular

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force by recruiting increasingly larger numbers of motor units based on axon size (Stuart and Enoka 1985). Increasing the force produced by a motor, however, requires feedback and a mechanical gear arrangement. The absence of actuators that have a realistic resemblance to biological muscle has been a challenge to the control of biomimetic robots. However, recent advances in sensor and artificial muscle technologies have made it feasible to consider development of robots, such as the robot lamprey, that are organized along more physiological principles (Ayers and Witting 2007). The lamprey is a primitive jawless fish whose sensory and locomotor neuronal systems, particularly its locomotor central pattern generator (CPG), a network of neurons and synapses that produce a rhythmic output, have been well studied (Buchanan and Grillner 1987, Ekeberg and Grillner 1999). The relative simplicity of the lamprey nervous system (in comparison with other vertebrates) makes the lamprey an ideal model organism for the study of biomimetics. Biomimetic robots differ from traditional robots as they are based on the biomechanics and neuroethology of walking, swimming and flying creatures in an attempt to capture the huge performance advantages that animals enjoy in the natural environment (Ayers 2004). In order to provide an advantage over traditional robots, biomimetic robots must demonstrate adaptability, flexibility, robustness and autonomous behavior.

The controllers implemented differ from behavior-based controllers (Brooks 1986, Arkin 1998) in that they mimic the neural circuitry and dynamics of biological nervous systems (Ayers *et al.* 2010). Neurons, by virtue of a palette of ion channels expressed in their membranes (Harris-Warrick 2002) exhibit a broad variety of conductance-based dynamics and these dynamics can be profoundly altered by neuromodulation (Harris-Warrick and Marder 1991). Interactions among these neurons are mediated by synapses that change their dynamic properties dependent on their use history (Bi and Poo 2001) and neuromodulation. The neuroethological analysis of innate action patterns allows many behavioral acts to be explained in terms of the properties and connectivity of their neuronal elements (Stein *et al.* 1997). These species rely primarily on sequences of innate behavioral acts that are both self-organizing and specified in the genome (Katz and Harris-Warrick 1999).

Traditional conductance-based models of neurons have been too computationally intensive to permit more than the simplest of networks and have not been permissive for the real-time control of robotic systems (Hammarlund and Ekeberg 1998). Recent advances in the application of nonlinear dynamics to neurons and synapses (Rabinovich *et al.* 2006) have established computational models of greatly reduced dimensionality that can be instantiated as analog computers (Pinto *et al.* 2000) or simulated on small DSP chips (Rulkov 2002, Ayers and Rulkov 2007).

We report progress on a robot that combines myomorphic actuators with a digital signal processor-based electronic nervous system to control adaptive behavior in response to input from neuromorphic sensors that utilize a labelled line code (Ayers *et al.* 2008). In contrast to previous implementations of electronic nervous systems (Reeve and Webb 2003, Lewis *et al.* 2003) our lamprey-based robot employs hundreds of simulated neurons and synapses distributed within the brain and the ten segmental CPGs. We will demonstrate that it is feasible to control a robot and achieve adaptive sensor driven behavior with such a network. In particular, we will demonstrate layered exteroceptive reflex networks that provide mechanisms for taxic behavior, behavioral transitions and sequencing.

2. Physical plant

The lamprey robot Fig. 1(a) consists of a cylindrical hull that houses the electronics and battery pack. The batteries are stacked in arrays of 3 in the bottom of the hull to provide roll plane stability,

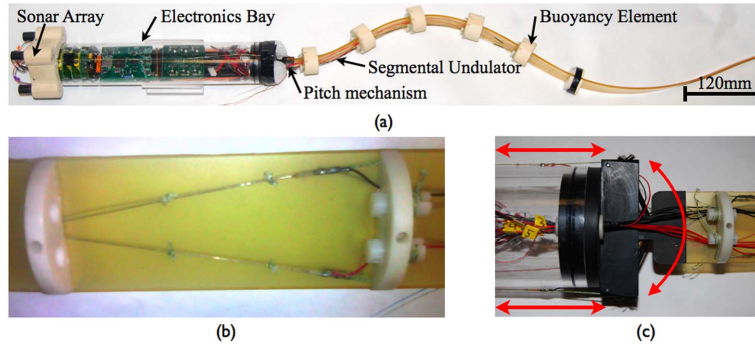


Fig. 1 (a) Lamprey Robot with sonar array, (b) Lateral view of tail segment showing nitinol actuator, Teflon vertebra and tensioning nuts and (c) Lateral view of pitch mechanism

eliminating the need for torsional actuators. A sheet of electromagnetic field foil is placed between the battery pack and electronics to eliminate sensor interference. The sonar array is positioned on the nose of the robot and is used to home on an acoustic beacon. The body axis is made from a polyurethane strip and is divided into five equal segments by Teflon™ vertebrae with a nitinol actuator on either side of the body axis for each segment. Each vertebra houses a mechanical tensioning system for the actuators and structures a cylindrical cross section for the body axis Fig. 1(b). The nitinol actuators are placed in a chevron formation for each segment and tied to the tail in four locations to reduce the chord length and ensuring correct curvature of the segment when actuated. Length adjustments are applied to the actuator via a Kevlar thread attached to a tensioning nut for each end. Neutral buoyancy is achieved by syntactic foam elements placed along the body axis at the back of the hull and sonar array housing. The pitch mechanism utilises dorsal and ventral nitinol actuators to flex the body axis relative to the hull. This flexion creates low-pressure areas below or above the hull, achieving dive and climb respectively Fig. 1(c).

The electronics board set for the lamprey robot (Fig. 2) consists of three components: the sensory systems, central nervous system (CNS) and neuromuscular interface. The sensory systems include a short baseline array (SBA) sonar system that is capable of triangulating and homing on an acoustic beacon (Hawat 2008), a compass that provides heading information, and a two-axis accelerometer that provides the robot with both tilt and acceleration information. The sensory data is then passed

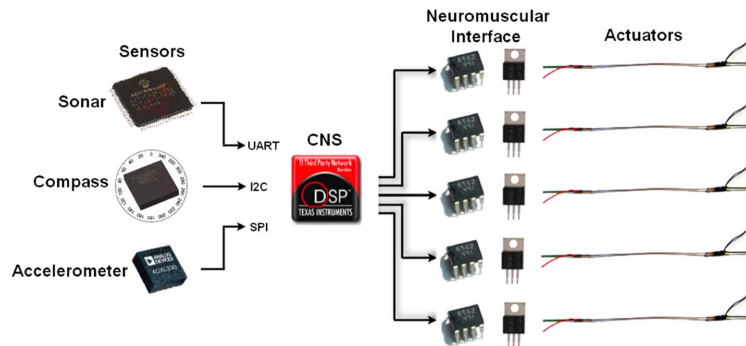


Fig. 2 Lamprey Robot hardware showing sensor integration, CNS and motor output through the neuromuscular interface

to the CNS using I²C and SPI protocols. The data from the sensory systems is used to control the command neurons that modulate the CPG that is responsible for the generation of the innate swimming pattern of the lamprey. The CNS runs a simulation of the neuronal model of the spiking-bursting activity of the lamprey CPG network in real-time and produces the array of output pulse signals triggered by action potentials from CNS motor neurons that control the current applied to the nitinol actuators.

The nitinol actuators are made from a shape memory alloy, nitinol. The material undergoes a crystalline structure change from martensite to denser austenite when heated, resulting in a shortening when heated and capability lengthening when cooled and deformed. The typical contraction time for this material is around 70 ms with a fall time to the martensite finish temperature of 100 ms when operating in 65°F water. When the actuator cools to the martensite finish temperature it can be deformed by the action of the antagonistic muscle. Construction of the actuators involves threading the nitinol through an etched Teflon™ tube, swaging either end with a stainless steel crimp and soldering on leads. The ends of the wire are then potted using shrink tubing and Aqua-Seal™.

The power source for the robot is a 12 v, 4500 mAh NiMh battery pack. The individual actuators each drain 1.5 A of current when activated. The total power requirements for the DSP chip and associated circuitry is around 100 mA during typical operation.

3. Electronic nervous system

The CPG model used in the lamprey robot Fig. 3(a) is derived from the network described in Buchanan and Grillner (1987). A central pattern generator (CPG) is a collection of neurons with excitatory (represented by triangles) and inhibitory (represented by filled circles) connections that

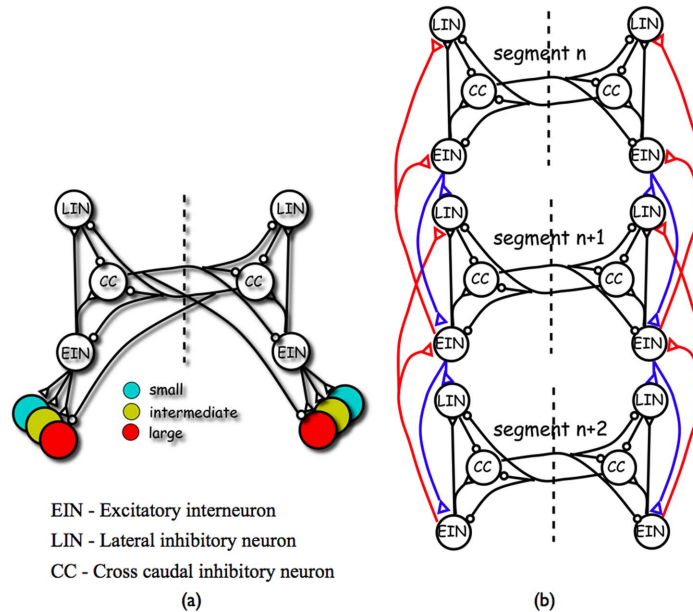


Fig. 3 (a) Lamprey CPG segment with amplitude recruitment and (b) Interconnected CPG segments with connections for forward and backward locomotion

produce an excellent replica of the rhythmic motor neuron output seen in behaving lamprey. The neurons and synapses in the lamprey CPG represent groupings of functional classes of neurons and synapses rather than individual neurons and synapses. Interneurons are neurons that connect from the sensory neurons to the motor neurons. Each lamprey CPG is made of two bilaterally symmetrical CPGs, consisting of excitatory interneurons (EIN), lateral inhibitory interneurons (LIN) and crossed caudal interneurons (CC). There is an excitatory connection from the EIN to the CC and LIN, an inhibitory connection from the LIN to the CC, and an inhibitory synapse from the CC of one hemisegment to the other side. In addition to these connections there is a set of anteriorly and posteriorly projecting excitatory connections from the EIN of one segment to the EIN and LIN of the next segment shown in red for anterior, and blue for posterior projections Fig. 3(b). The CPG left-right oscillation, generated by the post inhibitory rebound of the two CCs of each segment, allows the tail segments to bend left and then right. The EINs and LINs act on the CCs to regulate this oscillation and propagate the pattern down or up the tail resulting in forward or backward swimming, respectively. To drive the actuators the output of the EIN makes an excitatory connection onto small, medium and large motor neurons. These neurons are recruited in order to increase the amplitude of the swimming movements Fig. 3(a) by producing increasing pulse width duty cycles of current.

This project is focused on the development of a novel, computationally efficient approach to the replication of the signal processing and control functions involved in the complex neurobiological network of the lamprey undulatory locomotion system. Processing of sensory information and generation of control commands in the network occurs via spikes produced by the neurons interacting through synapses. The key element of our approach is the use of new phenomenological models of neurons and synapses derived in the form of a simple discrete time map (DTM) (Rulkov 2002, Shilnikov and Rulkov 2003, Rulkov *et al.* 2004). These models are capable of replicating the important spike pattern characteristics of specific neurons and the network spatio-temporal patterns.

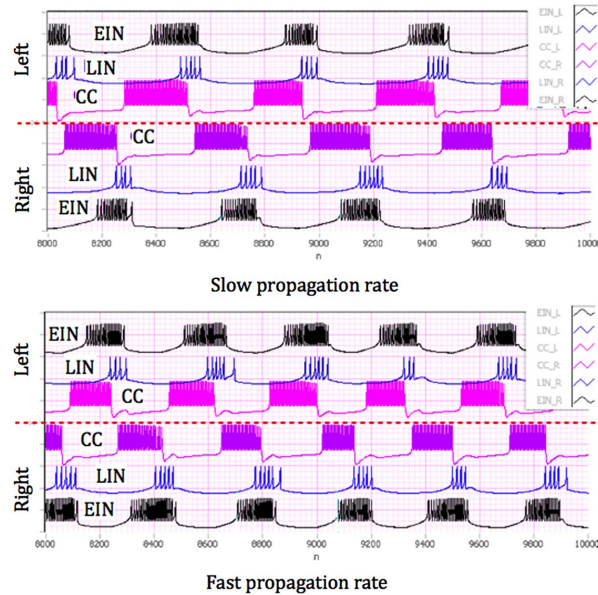


Fig. 4 The plots show the membrane voltage of the EIN, LIN and CC neurons for both hemisegments with the left side represented in the top three traces and the right side in the lower three traces of each plot for two oscillation rates, slow (top) and fast (bottom), leading to slow and fast swimming

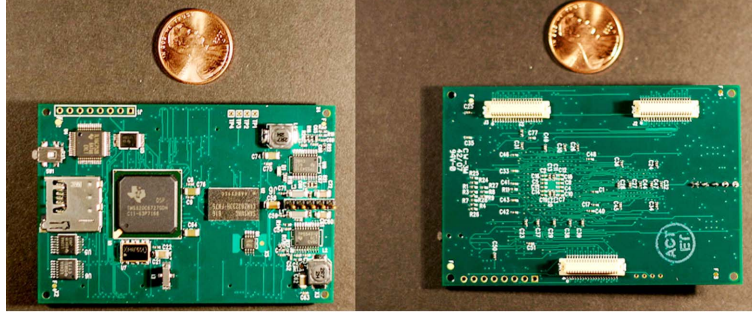


Fig. 5 Top and bottom views of the PC board of the custom TI DSP TMS320C6727 computer for the CNS

The output of one lamprey CPG segment implemented with the DTM models is shown in Fig. 4 for two different oscillation rates. The oscillation rate of the network is controlled by the level of excitation of EINs by command inputs in the segment. The higher the baseline of individual neurons the higher the frequency of the bursting activity that emerges in the segmental network. Note that the CC interneurons of the two sides alternate and coordinate a three-phase oscillation between the CC interneurons, the excitatory interneurons (EIN) and the lateral inhibitory interneurons (LIN). Spikes generated by EIN trigger the activity of motoneurons. It can be seen in Fig. 4 that activity in the EINs increases with the increase of the oscillation rate.

Our studies have shown (Ayers *et al.* 2008) that numerical simulation of the lamprey CPG network needed to control the lamprey biomimetic robot can be implemented in real time using a TI DSP chip. Our current configuration on a TI DSP TMS320C6727 running at 1.8 GHz is capable of emulating networks of up to 2000 neuron models in real-time. The custom DSP computer was built on a PC board 50 mm wide and 75 mm long. The top and bottom of the PC board are shown in Fig. 5. The three 42-pin connectors placed on the bottom of the board allow it to be connected to the sensor array board that relays the muscle driving signals to the actuators and supply the sensor inputs to the DSP. The DSP board contains power supplies for DSP and SD RAM (16MB) and a removable microSD card (2GB) for data collection.

The CPG model designed for the control of swimming patterns of the lamprey robot contains 10 segments, with every second segment exciting an actuator. This skipping of simulated segments provides the necessary intersegmental coordination to correctly drive the actuators. Depending on the excitation levels of head and tail segments the network can generate forward and backward undulations. To reduce the transient time for establishing the pattern of required motor-activity we initialize a command at the depolarized side of the network and then propagate its action along the network down to the hyperpolarized end with a constant propagation speed. The sequential excitation of the segments down the tail results in the characteristic flexion wave activity observed during locomotion. Fig. 6 shows the activity of the excitatory cells in the 10-segment network model of the CPG. The flexion wave activity corresponds to forward swimming undulations. The activity is initiated with a depolarization command propagating from the head (cells 1 and -1) toward the tail (cells 10 and -10), as shown in the top panel of Fig. 6. The bottom panel of Fig. 6 shows the activity patterns of the neurons located in the second segment of the network. One can see from Fig. 6 that a biologically analogous swimming pattern starts right after the command initialization and lasts until the activity is terminated with an inhibitory stop command.

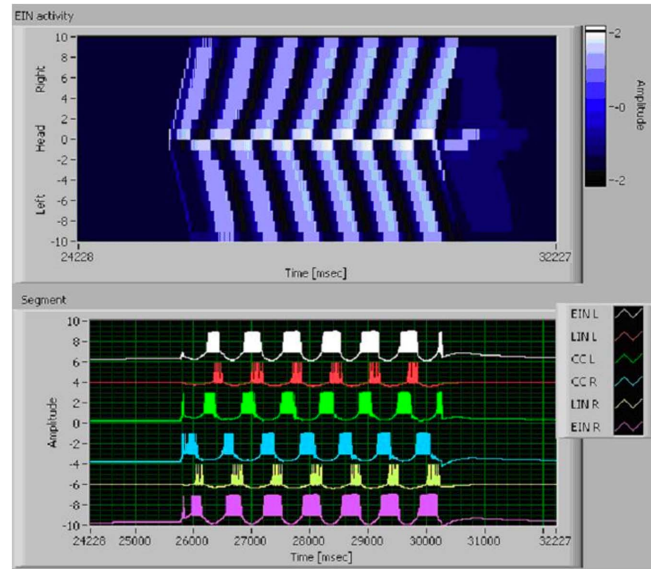


Fig. 6 Neuronal activity for undulations during a short-term forward movement in a LabVIEW simulation illustrating the relationship of interneuronal activity to the motor output. Top plot shows 10 segment simulation of the motor output. Bottom plot shows the corresponding membrane voltages of the interneurons of the CPG

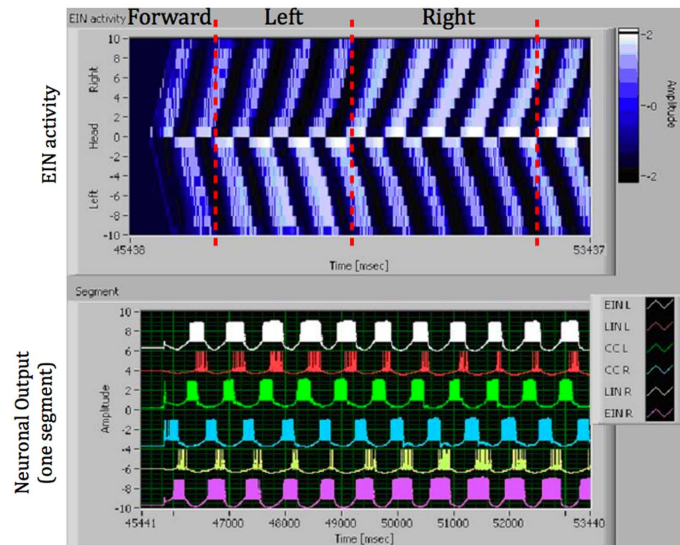


Fig. 7 Neuronal activities for undulations during a sequence of straightforward swimming, left turn and then right turn. Top plot shows a 10-segment simulation of the motor output. Bottom plot shows the corresponding membrane voltages for a single CPG segment

The patterns of turning activity are controlled by the asymmetric excitation of the neurons in the left and right hemisegments. The turn command sets a higher level of depolarization in excitatory neurons (EINs) at the hemisegments located on the side to which the robot turns.

The result of the bias to the left or right during forward swimming is shown in Fig. 7. More specifically Fig. 7 shows the following sequences (with a cycle representing the period between two successive onsets of bursting in a given actuator): 1) initialization of straight forward swimming activity for 2 cycles; 2) turning to the left for 3 cycles; 3) turning to the right for 4 cycles. One can see that transient time for reaction to the turning commands is very short.

In contrast to the rapid response to turn commands, a change in the swimming direction requires a much longer transient time if one simply switches from the forward command to the backward. As shown in Fig. 8 (top panel), even nine cycles of the CPG model is still not enough to complete the transient changing from forward to backward swimming. Usually this transient takes about 20-25 cycles, showing the inherent stability to perturbation of the CPG network.

One way to speed up the process of direction change is to turn off the undulations with strong inhibition and let the network get to the quiet state before sending a command for the opposite swimming direction. In this case after the stop, the network loses the memory of phase relation between the segments very quickly and, when the motions are resumed, the new phase relation is set up by the direction command at the initialization stage, see Fig. 8 (bottom panel).

Data collected from swim trials of the robot lamprey during forward swimming, forward swimming during a left turn and backward swimming are shown in Figs. 9(a)-(c). These figures illustrate several features of the motor output. Forward swimming as seen in Fig. 9(a) shows the output to the two sides rigidly alternating during forward swimming with a propagation time roughly equal to the period of swimming. Yawing to the right, see Fig. 9(b), is mediated by modulation of the motor output to one side by increasing the pulse width duty cycle of current applied to the nitinol actuators. Finally backward swimming shown in Fig. 9(c) is initiated by generating flexion waves that propagate from rear to front.

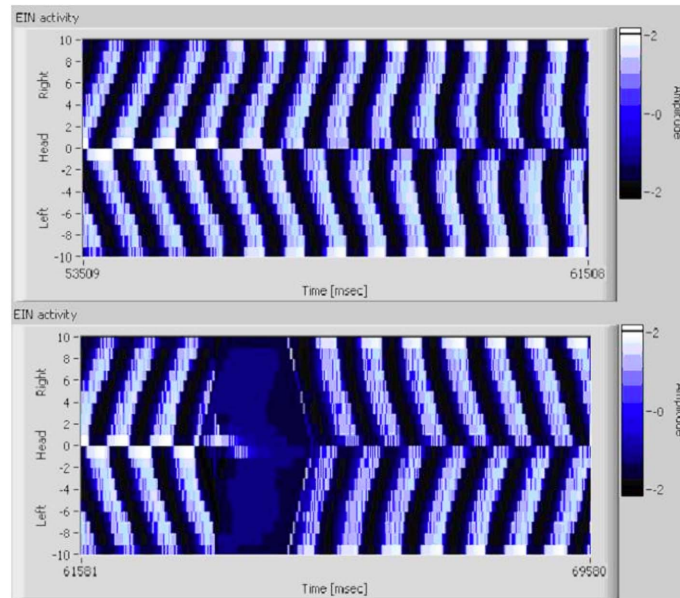


Fig. 8 Motor output plots of transient behavior of the model during the change from forward to backward swimming. Continuous transient obtained without interruption of undulations (top panel) and transient in the regime forward-stop-backward (bottom panel)

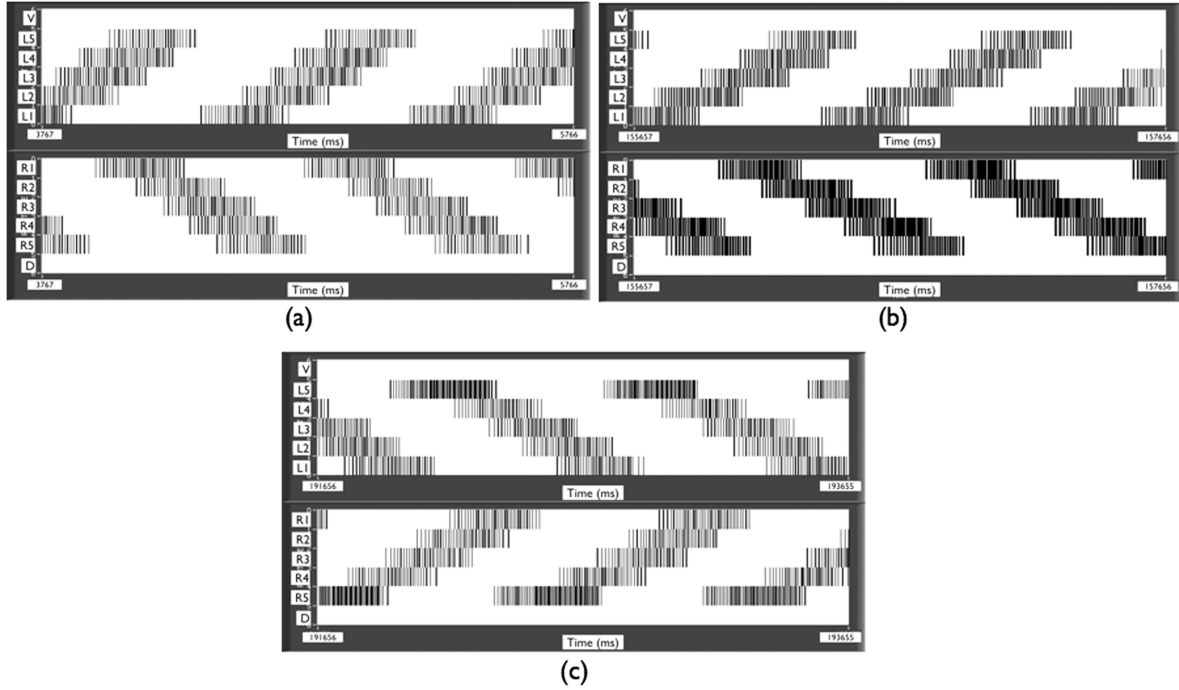


Fig. 9 Motor output to actuators, each vertical line represents a ‘spike’ sent to the actuators. (a) Forward swimming, (b) forward swim with left turn and (c) Backward swimming. L1-5 denote left side actuators from head to tail, R1-5 denote right side actuators from head to tail. D and V are the dorsal and ventral actuators used to dive and climb. This data corresponds to an iteration rate of 150 ms with pulse duration of 3 iterations. The iteration rate sets the timing characteristics of the CPG network activity and is selected to match the hydrodynamic properties of the robot. The pulse duration controls the actuator force in the response to each spike

4. The sensory system

The Sensor board (Fig. 10) connects to the CNS DSP board via three 42-pin connectors. It is populated with a digital compass, accelerometer and sonar DSP chip. It has both a magnetic power reset and magnetic reset switch. The magnetic power reset allows the neuron DSP board to be switched off while the battery is plugged in saving battery power during inactive periods. When the device is ready to be deployed the magnet holding the switch off is removed, powering up the device. The magnetic reset switch can be used to reset the device to a known state. The 15-pin connector on the right carries the spike train information that drives the actuators. The 10-pin connector on the left mounts the sonar array stack (Fig. 11). This stack is responsible for the buffering, filtering and amplification of the hydrophone signal. It also contains the power circuitry to step down the 12VDC main battery to the 3VDC, 5VDC and -5VDC required to operate the other integrated circuits (ICs).

The Sonar DSP board can be reprogrammed via the sonar prg port. This is done via a connection from any Microchip programmer (ICD2TM, ICD3TM, Real IceTM) while power is supplied via the 3.3 V line. The maximum power consumption of the sonar DSP is about 50 mA.

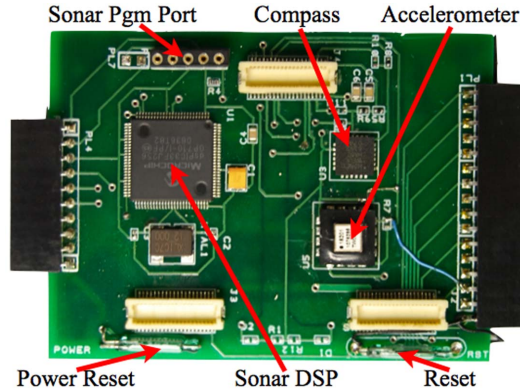


Fig. 10 Sensor array board with sonar DSP, compass and accelerometer. The connector on the left of this board receives the three filtered analog signals from the hydrophones via A1-A3, the 3.3VDC and 5VDC to run the sonar and CNS DSPs respectively and outputs the SPI link to the PGA. The connector on the right side carries the outputs that drive the actuators. The three 42 pin connectors join the board to the CNS DSP board

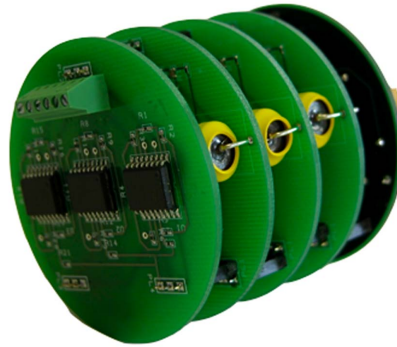


Fig. 11 The Sonar processing stack is made of five stages. From left to right the first stage is the buffer amplifier for the three hydrophone channels. The next three stages each hold a band pass filter, one for each channel. The final stage comprises the PGA and power circuitry delivering 3VDC, 5VDC and -5VDC

The layered reflex circuits controlling the behavior of the robot fall into three classes: impediment compensation, pitch-plane modulation and yaw-plane modulation (Fig. 12). A reflex consists of a sensory releaser that is connected via interneurons to descending command neurons that act on the motor system. Impediment compensation is mediated by three cases of impediment reflexes. These reflexes address being impeded during start up (i.e., reduced translational acceleration), being impeded by swimming into seaweed (slow deceleration) and colliding with a hard object like a rock (high deceleration). Responses to impeded acceleration and rock collision are mediated by a collision command that triggers a backup and restart, while responses to slow deceleration activate the fast swimming and flexion amplitude modulation commands. The acceleration components used to sense impediments are indicated in Fig. 12(a).

Pitch plane modulation controls the dorsal and ventral actuators that pitch the hull relative to the undulator to mediate dive and climb. The inclinometer and short baseline array (SBA) circuits

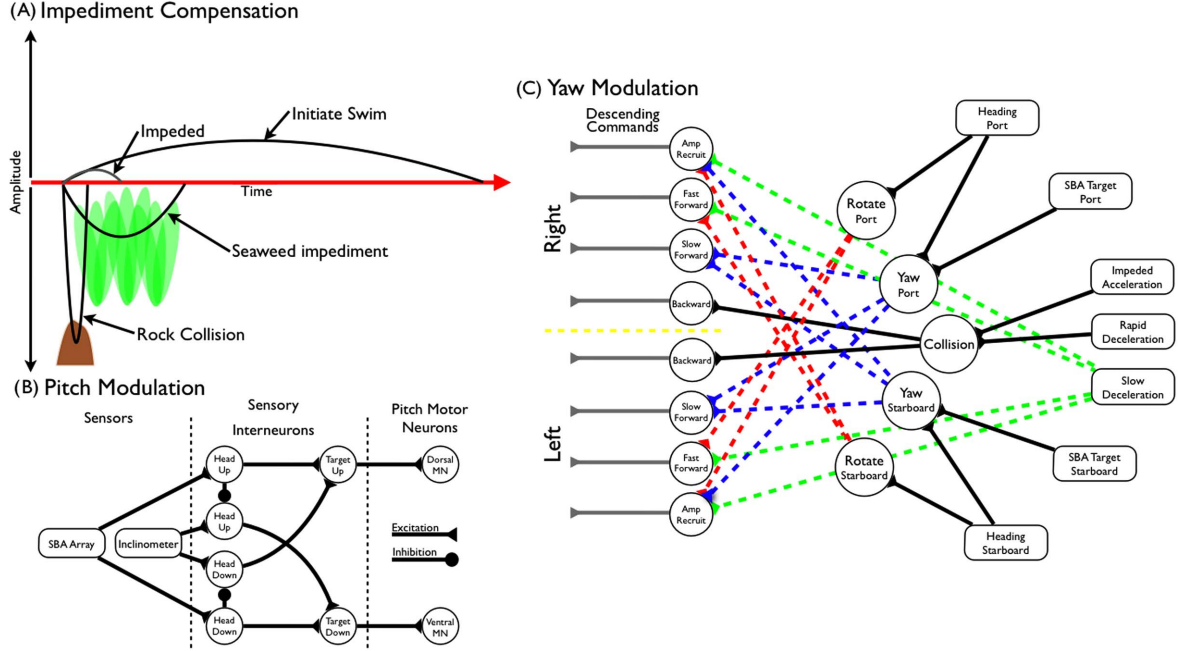


Fig. 12 (a) Conceptual representation of acceleration profiles seen during operation, (b) Neural circuit for pitch modulation and (c) Yaw modulation

operate through parallel interneurons that activate the motor neurons Fig. 12(b). The pitch plane component of the SBA target signal overrides the inclinometer circuitry allowing the robot to dive and climb to home on the sonar transducer.

Parallel pathways from the heading control circuit mediate yaw plane modulation. One pathway compares the desired compass heading with the actual compass heading to generating a bias signal providing course correction. The other pathway carries the SBA signal and as in pitch modulation overrides the heading circuitry allowing homing on the sonar transducer Fig. 12(c) if a signal is present.

Transitioning from analog sensory information to a neuronal signal is achieved by the range fractionation circuitry (Fig. 13). In the case of the accelerometer, as the amplitude of the signal increases a specific neuron coding for that range is activated, inhibiting lower threshold neurons. In the example shown in Fig. 13 three neurons, coded for high (H), medium (M) and low (L), are used to represent varying intensities of acceleration. L has the lowest threshold and fires for slow accelerations such as swim initiation. M is triggered for medium decelerations as in the case of seaweed impeding motion, and H is triggered for high rates of deceleration, indicating a rock collision. In this way, coded information can be sent to the locomotor CPG through the command neurons allowing the robot to autonomously navigate its surroundings.

Currently the robot lamprey is provided with overhead commands such as stop, swim, turn, dive and climb via a BluetoothTM link operating at a baud rate of 115200 bps. This link also streams the neural and sensory data from the robot to a file on the computer to be used for analysis of its behavior at a later date.

We are currently moving from the BluetoothTM communications protocol to a system utilising the

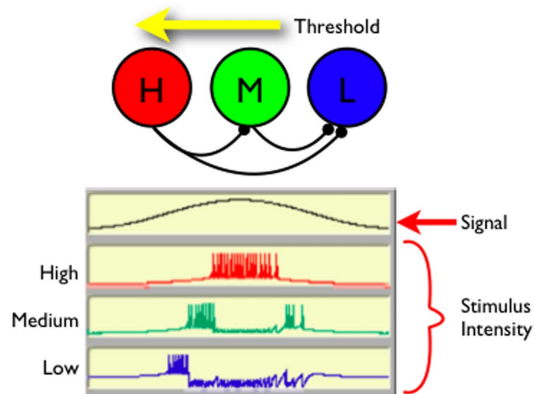


Fig. 13 Range fractionation of sensory input. As the signal amplitude changes specific neurons are triggered for low (L), medium (M) and high (H) accelerations

SBA for supervisory commands. We are currently capable of receiving four bits of information in the form of four frequencies that are broadcasted on top of the 10.5 khz signal from the sonar transducer.

5. Conclusions

Robots are traditionally controlled algorithmically by computer programs such as state machines. Although the neurons in the lamprey robot are simulated on a digital computer, they are programmed with the dynamics and connectivity of neurons and synapses utilizing biological control mechanisms rather than algorithmic control. The approach we have instantiated has two major advantages. First, because the neurons are simulated with a reduced dimensionality nonlinear dynamical model, large aggregates can be simulated in real time. Second, because the controller is based on nonlinear neuronal network models it rapidly returns to stability following perturbation (Rabinovich *et al.* 2006).

The hierarchical arrangement with low level commands (forward swimming, left amplitude modulation, etc) activated together by higher order interneurons (rotate, etc) allows different behavioral acts to be superimposed as well as provide discrete command loci. In general all exteroceptive networks are logically “on” but they are not always receiving the appropriate sensory releaser to power them up. We have included some inhibitory connectivity to maintain a hierarchy of behaviors. For example, for the system to climb or dive in response to the inclination signal from the short baseline array, it much inhibit the pitch pathway from the inclinometer which has the goal of keeping the hull level.

By adding controls for task switching, (i.e., from forward to backward swimming) we found that the system could not make a rapid transition from forward to backward swimming, but required several cycles of swim movements. It was found that complete inhibition followed by a restart was necessary to produce rapid transitions. We are performing ongoing integration of these reflexes, both through simulation of these circuits in LabVIEW as well as annealing of the C code for optimal operation on the DSP.

We have a library of films of behaving adult lamprey in the Merrimack River and in our test pond with seaweed obstacles. We plan to conduct a kinematic analysis of the undulatory behavior of the

robot and directly compare it with data collected from real lamprey. This comparative analysis of the kinematics will allow us to fine-tune the locomotor CPG, optimizing its performance and provide confirmation of the lamprey CPG model.

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