Biomimetic approaches to the control of underwater walking machines

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We have developed a biomimetic robot based on the American lobster. The robot is designed to achieve the performance advantages of the animal model by adopting biomechanical features and neurobiological control principles. Three types of controllers are described. The first is a state machine based on the connectivity and dynamics of the lobster central pattern generator (CPG). The state machine controls myomorphic actuators based on shape memory alloys (SMAs) and responds to environmental perturbation through sensors that employ a labelled-line code. The controller supports a library of action patterns and exteroceptive reflexes to mediate tactile navigation, obstacle negotiation and adaptation to surge. We are extending this controller to neuronal network-based models. A second type of leg CPG is based on synaptic networks of electronic neurons and has been adapted to control the SMA actuated leg. A brain is being developed using layered reflexes based on discrete time map-based neurons.

Keywords: lobster; robot; biomimetic; behaviour; underwater; electronic neuron

1. Introduction

There has been considerable interest in the development of biomimetic robots based on animal models (Taubes 2000). Arthropods have long been the models for the study of the mechanisms of generation of locomotion and navigation (Evoy & Ayers 1982; Bassler & Buschges 1998; Durr et al. 2004; Ritzmann et al. 2004). We have developed an ambulating underwater robot based on the biomechanics and behavioural set of the American lobster (Ayers 2004b). These robots are intended for use in shallow water remote-sensing operations (Ayers 2000). The behavioural set of the lobster represents a proven solution of navigation and adaptation in these complex and often turbulent environments (Atema & Voigt 1995). Implementation of an underwater vehicle based on the lobster (figure 1) presents unique problems with regard to actuation, sensing, hydrodynamics and particularly in adaptive biomimetic control (Ayers 2004b). The controllers that we have developed are based on the neurophysiology and behaviour of the animal model (Ayers 2002a, 2004a), and range from finite state machines to electronic neuronal networks.
Although the understanding of the cellular mechanisms of operation of the lobster nervous system is advanced (Selverston 1993), the understanding of the higher order control mechanisms of navigation, obstacle negotiation and investigative behaviour is incomplete (Factor 1995; Cattaert & Le Ray 2001). The actual test of the role of interneurons in the control of behaviour requires recording from the identified elements of the underlying neuronal circuitry in freely behaving animals and presents enormous technical difficulties (Pinsker & Ayers 1983). The embodiment of neuronal circuits in a behavioural controller becomes a model to test the underlying hypotheses of how the nervous system controls behaviour (Webb 2000, 2001). For a robotic instantiation to model animal behaviour, it must both approximate the biomechanics as well as the dynamics of the underlying neuronal components (Abarbanel et al. 2004).

2. Lobster biomechanics

When compared with terrestrial arthropods (Bassler & Buschges 1998), underwater walking arthropods, e.g. the lobster, face a set of unique challenges. First, lobsters must deal with a variety of often complex bottom types such as sand, cobble, rock fields or eel grass beds (Campbell & Stasko 1986). Dealing with obstacles in the environment requires high manoeuvrability and lobsters have the ability to change their walking direction on a step-by-step basis (Ayers & Davis 1977b). Rapid rotations in place are mediated by walking forward on one side and backward on the other (Copp & Jamon 2001). The rotation is enhanced by close placement of legs on the thorax (figure 2a). During walking, lobsters can yaw by walking more rapidly on one side relative to the other (Domenici et al. 1998) and/or differences in amplitude of movements on the two sides (Cruse & Saavedra 1996) or a combination of these mechanisms.

Figure 1. The NU/DARPA/ONR lobster robot. The vehicle is based on a watertight electronics bay and associated battery pack. Actuators include eight three degrees of freedom legs, as well as claw- and abdomen-like hydrodynamic control surfaces. Motor-driven antennae are active flow surfaces.
Second, the mass distribution of the lobsters differs profoundly from that of insects with the large chelipeds and abdomen extending rostrally and caudally with regard to a comparably sized thorax (figure 2a). Unlike terrestrial organisms which must bear their entire mass, lobsters are buoyed by seawater and weigh about one-eighth of their mass in air. Thus, lateral hydrodynamic forces can be greater than vertical gravitational forces (Martinez 2001). Decapods use their chelipeds and abdomen as hydrodynamic control surfaces to achieve stability in the pitch plane (Maude & Williams 1983). They also take advantage of a splayed posture of the walking legs to provide stability in the roll plane. An additional consequence of low relative mass is the reduced traction during surge. The only contact point of the body with substrate is the dactyls, and when the gravitational forces are low, traction is reduced. Having an additional pair of legs when compared with insects may be an adaptation to the need for an increased traction. When faced with flow and surge, lobsters and crayfish may also elevate their abdomen and depress their claws (figure 2b), to generate a thrust vector into the substrate, substantially increasing traction.

3. Lobster locomotory movements

The walking movements of lobster legs occur primarily around three limb joints (Ayers & Davis 1977b). Cyclic elevation/depression movements of the coxo-basal (CB) joint (figure 3a–c), underlie the swing and stance phase of walking...
in all directions (figure 3a–c). During forward and backward walking, translational propulsive forces are generated by cyclic movements of the thoraco-coxal (ThC) joint (figure 3d–f). The swing phase of the ThC joint is coupled with cyclic elevation (early swing) and depression (late swing) of the CB joint, while the stance phase is coupled with the antigravity (relatively isometric) phase of the CB depression movement. During lateral walking, the translational movements are generated by cyclic movements of the mero-carpopodite (MC) joint and coordinated with CB joint movements in an analogous fashion (figure 3g–i). During forward and backward walking, the antagonist extensor and flexor muscles of the MC joint are coactivated (figure 3g) to keep the joint stiff (Ayers & Clarac 1978), while the ThC joint is stiffened throughout the step cycle during lateral walking (figure 3c).

Figure 3. Limb movement's underlying walking in different directions. (a–c) Coxo-basal joint movements; (d–f) thoraco-coxal joint movements and (g–i) mero-carpopodite joint movements. (a, d and g) indicate joint movements during forward (closed circles) and backward (open circles) walking. (b, e and h) indicate joint movements during lateral leading (closed circles) and trailing (open circles) walking. (j) Three movement phases of the step cycle. (k) Epochs of muscle activity in the four primary motor synergies.
4. Neurobiology of lobster locomotion

Studies over the past 50 years have demonstrated that the innate behaviour of animals is generated by the distributed networks of neurons in the central nervous system (Delcomyn 1980). Lobsters and crayfish served as important model systems in the development of the command neuron, coordinating neuron and central pattern generator (CPG) model of the organization of innate motor systems (Kennedy & Davis 1977; Pearson 1993). The basis of this model is that the locomotory movements of different limbs are controlled by segmental CPGs resident in the spinal cord or ganglionic chain (Sillar et al. 1986; Selverston 1999). The CPGs of different body segments are coordinated among themselves by neuronal populations, termed coordinating systems, that pass information from a governing oscillator to a governed oscillator to maintain gait (Stein 1978; Namba & Mulloney 1999). These systems are turned on and modulated by a descending system of command neurons (Bowerman & Larimer 1974). The command neurons can operate by direct synaptic activation (Larimer 2000) or through parametric control by neuromodulators (Harris-Warrick & Marder 1991).

These central mechanisms are subject to ongoing modulation by sensory feedback (Pearson 1995). Proprioceptive reflexes operate on segmental CPGs to alter the amplitude or reset the phase of ongoing central programs (Stein 1978). Amplitude modulating reflexes occur when the sensory feedback operates at the level of the motor synergies of motor neurons (figure 3b). Amplitude modulation affects the number, size and discharge frequency of the active motor neurons. Phase-modulating reflexes operate at the level of the neuronal oscillator and can perturb an ongoing rhythm on a cycle-by-cycle basis (Pinsker & Ayers 1983). Intersegmental exteroceptive reflexes modulate responses of the whole animal in response to optical flow, gravity, chemosensory or other external inputs (Grasso 2001).

5. Biomimetic robot controllers

To approach the behavioural capabilities of the model organism, we base the controller on existing models of the underlying lobster neuronal circuitry which are incomplete (Chrachri & Clarac 1989). The intact walking pattern has three phases with a late swing bringing the limb back into contact with the substrate. Several investigators (Sillar & Skorupski 1986; Chrachri & Clarac 1990) have developed preparations of the isolated crayfish thoracic chain, which generated elements of the walking motor program that differed from the walking motor programs observed in vivo. In particular, the central rhythm consisted of a rigid alternation between an early swing-like state and a stance state with no intervening late swing. It would appear that the walking commands (Bowerman & Larimer 1974) are essential to evoke the complete rhythm that necessarily includes a late swing phase. Test of this hypothesis requires stimulation of walking commands in a deafferented preparation, an experiment that has yet to be performed. The role of walking commands can be inferred indirectly (Ayers & Davis 1977). The most parsimonious model relies on a network of four interneurons to generate the four basic synergies forming the step cycle (figures 3k and 4a). This connectivity is consistent with the existing connectivity maps (Chrachri & Clarac 1989). Our simulations indicate that the
commands may select the programs for walking in different directions by altering connectivity within a common synaptic network (Chrachri & Clarac 1989). This connectivity is capable of explaining both the rapid changes in walking direction seen in behaving specimens as well as diagonal walking, where both the ThC and MC joints participate in the generation of propulsive forces (Ayers 2002a). Here, inter-joint reflexes serve to reinforce multi-joint synergies (Ayers & Davis 1977a, 1978). A further enigma of the walking system is that ‘passive traction’ is necessary for expression of command neuron evoked walking (Bowerman & Larimer 1974b). A plausible explanation of this observation is that load-sensitive feedback during the stance phase, resulting from the impediment of limb movement, overwhelmingly phase delays the subsequent swing phase, so as to damp the relatively weak single neuron evoked central oscillation (Pinsker & Ayers 1983). This control model differs from the predominate control model for insects that relies on independent oscillators for the three analogous joints (Buschges 2005). The insect model relies on segmental reflexes to mediate inter-joint coordination and although

Figure 4. Neuronal circuit modules of the lobster locomotory system. (a) Modular organization of the segmental circuitry. CPG, central pattern generator; CoN, coordinating system; CN, command system. The open circles on the CoNs imply inhibitory synaptic influences and the open triangles associated with the CNs imply parametric excitatory influences. (b) Details of the segmental CPG and associated reflex pathways. Amplitude-modulating reflexes feed back from the sensor to motor synergies, while phase-modulating reflexes feed back to the neuronal oscillator. (c) Exteroceptive reflexes are mediated by bilaterally symmetric inputs to contralateral CPGs or to bias segmental CPGs as in the control of pitch and roll by antigravity synergies.
such reflexes are present in lobsters (Ayers & Davis 1977a), they only respond to leg movements and not positions and therefore appear to play a role in reinforcing coupling (Ayers & Davis 1978) rather than mediating coupling which must be flexible to permit walking in different directions.

The primary requirements for the controller are that it generates a reasonable replica of the lobster motor programs, has the hooks necessary to mediate the adaptational capabilities of the animal model and operates in real time using relatively low-power microcontrollers. This control model differs from behavioural-based control models (Brooks 1986) since the same neuronal control structures can be used in a variety of combinations and contexts to mediate different behavioural acts. Thus, behavioural processes such as oscillation, superposition, sequencing and choice emerge as a result of network connectivity and dynamics of the underlying neuronal circuit modules (figure 4) as opposed to behavioural schema (Arkin 1998).

The existing vehicle1 is based on a network organization (figure 5a), in which a set of finite state machines (figure 5b) implement both the organizational rules of the neuronal circuit and the observed temporal structure of the motor programs (Ayers & Davis 1977b). The organizational components of the state machines are the neuronal oscillator generating the stepping pattern, the pattern generator

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1 A movie of the vehicle in operation is available online at: http://www.neurotechnology.neu.edu/latmaneuvering.html.
modulating coordination to specify the direction of walking and the recruiters controlling the amplitude of the motor output, and the motor synergies that directly activate actuators (figure 5b). There are several internal state variables that specify details of the walking program. These state variables are quantized into small number states. For example, walking speed has four states (low, medium, high and load), based on characteristic walking speeds of the animal model (Scrivener 1971). Other leg state variables include walking direction, intensity and height. Walking in opposite directions (i.e. forward versus backward) is mutually exclusive, but combinations of forward or backward and lateral walking can generate hybrid behaviour such as diagonal walking. The walking speed state acts on the neuronal oscillator and propulsive recruiter specific to the direction of walking. The walking direction acts at the pattern generator level and intensity and height act at the level of the antigravity and propulsive recruiters. Changes in pitch and roll are mediated by biasing the height state for the different segments or sides. Several other concatenated state machines control the posture of the claw- and abdomen-like hydrodynamic control surfaces and the antennae.

6. Myomorphic actuators

The most critical components in achieving animal-like behaviour in biomimetic robots are the actuators. The most common actuators used in contemporary robots are gear head motors. Motors mounted on moving appendages generate high inertial masses and require relatively complex electronic interfaces. The neuromuscular systems of animals use inherently different forms of control. Animals make joint movements by alternating contractions of antagonist muscles and regulate joint stiffness by coactivation of antagonist muscles. Contractions are graded by sequential recruitment of motor neurons of the order of their size which is proportional to their efferent effect (Davis 1971; Stuart & Enoka 1985).

Several forms of artificial muscle exist (Ayers et al. 2002). We have adapted nitinol shape memory alloy (SMA) wires as artificial muscle for underwater operation (Witting & Safak 2002). The individual actuators (figure 6a) consist of a segment of acid-etched nitinol wire that have current source leads attached with stainless steel crimp connectors around a loop of nitinol at the end. For thermal and electric insulation, the body of the nitinol wire is covered with a sheath of etched Teflon tubing. Kevlar connecting ‘tendons’ are threaded through the loop and screw adjusters are cemented to the crimp connectors. The exposed nitinol is then sealed with Aquaseal.

The shape memory effect is used to generate a contraction/relaxation cycle. During manufacture, individual modules are annealed at high temperature (greater than 600°C) to convert all of the nitinol to the dense austenite state (figure 6b). When cooled, the modules can be strained into the less dense martensite state with length changes up to 8% (Duering et al. 1990). Resistively heating the wire with applied electrical current up to 70°C proportionally converts the nitinol from martensite to austenite with an associated contraction (figure 6c). The modules are then trained by a series of active contractions against a graduated mass until they achieve a highly reproducible stroke of approximately 4.8% over their austenite length.
In the robot, nitinol actuators are employed in antagonistic pairs. Seawater surrounding the modules (figure 7a) ensures rapid conversion from austenite to martensite. In operation, the active contraction of one module stretches the antagonist and vice versa (figure 6d). Active contraction of both modules together compresses a series spring and stiffens the joint (figure 6e).

When operated under water, SMAs present several advantages. First, they are extremely force dense, producing stresses of the order of 10 N. Second, when cooled by seawater to speed the conversion from austenite to martensite, they have an acceptable dynamic range and antagonist pairs can make repetitive contractions at over 2 Hz. Third, they can be activated by trains of current pulses to grade force in an analogous fashion to the way that motor neurons activate animal muscle (figure 6c).

Crustaceans typically have a small number of motor neurons per muscle (Atwood 1973). They grade muscular force by means of size principle of recruitment, where motor units are recruited in the order of size to achieve stronger contractions. In the lobster robot, we use quantized pulse width duty cycle modulation to realize size ordered recruitment. The portion of nitinol that converts from martensite to austenite is proportional to the duty cycle and

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Figure 6. Nitinol actuators. (a) Individual SMA artificial muscle module; (b) shape memory effect and (c) relationship of contraction dynamics to current duty cycle. The traces represent the position of a 1 kg weight lifted by a muscle module. An upward displacement of the upper trace represents shortening of the muscle. The percentages indicate the proportion of time (duty cycle) that the electrical current is applied to the muscle. (d) Movement control with nitinol actuators. (e) Stiffness control with nitinol actuators.
increases both the amplitude and velocity of the contraction (figure 6c). For each muscle, we specify a low, medium and high recruitment level. Each level corresponds to a pulse-width duty cycle specified in a lookup table. When the intensity of behaviour is changed, the duty cycle associated with each recruitment level is changed. In practice, the duty cycle necessary to initiate contractions is higher than that necessary to maintain contractions, so the trains which activate a muscle consist of a brief (150 ms) segment at high duty cycle followed by the remainder of the train at the duty cycle appropriate to the speed of walking.

The muscle modules actuate a three degrees of freedom walking leg (figure 7a). The leg is bolted to the hull by a support that houses a vertical capstan (figure 7b) forming a robotic analogue of the lobster ThC joint. The capstan is actuated by a pair of muscle modules housed in adjacent vertical tubes (figure 7a). Screw mounts and a pair of springs in series with the muscle modules
allow adjustment. In the absence of proprioception, the springs allow the modules to contract even when joint movements are physically constrained, thus preventing the over-stressing of the nitinol (which can eliminate the shape memory effect; Duering et al. 1990). The CB joint pivots in the vertical capstan and is actuated by a pair of modules that span the segment between the CB and MC joints. A pair of modules that span the segment between the MC joint and the tip of the leg, in turn, actuates the MC joint. Owing to the length of the leg, the forces at the tip of the leg generated by the ThC joint are typically of the order of 0.8 N. During load compensation, while walking into flow, the angle of the MC joint can be reduced to shorten the lever and provide enhanced translational force.

7. Electronics

The current lobster robot is based on a backplane modular board arrangement (figure 5). The motherboard houses the serial bus, voltage regulators for the low-current electronics, the compass and inclinometers. During debugging, the vehicle can be operated by an external laptop (figure 5a) through a RF modem connected to a float above the vehicle in a test pool (figure 5b).

For general use, the robot can be controlled by an embedded microcontroller (figure 8c). The controller application has a laptop version and an embedded microcontroller version. The embedded version is a subset of the laptop version with all graphical user interface elements removed and linked to a runtime.
library supporting the microcontroller (3V Motorola 68020, Persistor Instruments, Inc., Bourne, MA). Both the laptop and the microcontroller communicate to the other boards through a serial bus.

Four leg-driver boards control the nitinol actuators of the walking legs. Each board has a PIC16 microcontroller (Microchip Technology Inc., Chandler, Arizona) that receives commands from the laptop or microcontroller and provides pulse-width modulated (PWM) current trains to activate the muscles of the two legs of one segment. The commands sent to the driver boards include control bytes specifying a leg, a muscle and either one of the three recruitment levels or stop. The three recruitment levels (low, medium and high) specify three discrete PWM duty cycles, which correspond to small, medium and large motor neurons in the crustacean neuromuscular recruitment scheme (Davis 1971). The duty cycles associated with each recruitment level can be programmatically changed on the fly to alter the intensity of the motor output. For example, the levels of low, 10%; med, 30% and high, 70% might be increased to low, 20%; med, 40% and high, 80%. Thus, the leg-driver board receives a byte to turn on a muscle at a particular duty cycle level and it continues applying a current pulse train until it receives a stop byte. During a pulse train, the duty cycle can also be switched from a high (pre-heating) duty cycle to one more appropriate for the direction of walking.

A multifunction board controls the DC motors that control the posture of the claw- and abdomen-like hydrodynamic control surfaces and the antennae. This board also houses sensor electronics for the antennae and bump sensors. Finally, a sonar communication board allows the robot to receive 64 byte commands through a sonar transducer. The sonar commands consist of a 30 kHz tone followed by a 40 kHz tone. The interval between these tones is discretized by 15 ms into eight intervals. The sonar board has a tuned filter for the 30 kHz tone and upon reception starts a timer that determines the latency to a corresponding 40 kHz tone from another tuned filter. The tone pairs are sent in two pairs giving rise to 64 possible command codes.

The robot has an external power supply that consists of four parallel sets of five NiMH HR210AA batteries (Panasonic Industrial Company, Elgin, IL) in series. Each set of batteries powers a pair of legs to reduce the effect of the low-resistive load of large numbers of active nitinol elements. The current required by the motherboard and the low-current subsystems of the other leg driver boards are powered through one of these battery legs.

### 8. Reactive control

The behaviour of the robot is presently specified by a set of nine internal state variables having two to five states. These state variables specify the action of the legs, the posture of the claw- and tail-like hydrodynamic control surfaces and the action of the antennae. These state variables are derived from the observation that a population of command neurons, each of which specifies movement or the position of the appendages (figure 9a), controls the behaviour of crayfish (Bowerman 1974a,b). For the purposes of control of the robot, we use a reduced number of states (figure 9b). The complete set of internal state variables currently implemented includes the following.
— **Thorax pitch.** Rostrum up, level and rostrum down.

— **Thorax roll.** Left up, level and right up.

— **Thorax height.** High, normal and low.

— **Thorax yaw.** Hard left, easy left, straight, easy right and hard right.

— **Walking direction.** Standing, forward, backward and lateral leading lateral trailing.

— **Walking speed.** Slow, medium, fast, load and stop.

— **Chelae pitch.** Up, normal, down and low.

— **Antennae yaw.** Protracted, normal, lateral and retracted.

— **Abdominal pitch.** Extended, elevated, normal, depressed and flexed.

The behaviour controller for these robots is organized at two levels. At the lowest level, sensors modulate internal state variables directly to generate adaptive responses. At the highest level, the controller is organized around behavioural libraries and a sequencer. The sequencer maintains the state of the
vehicle by switching between different command states in a temporal sequence
specified by both orientation and magnitude of sensor input and the response
patterns specified by the behavioural libraries.

To generate behaviour libraries, movies of behaving lobsters are subjected to
reverse animation (Ayers 2000a). A program allows an investigator to step
through a movie on a frame-by-frame basis and specify the state of the animal
with a panel of radio buttons (figure 9c). The state of each task group of the
animal is approximated as one of the set of states (figure 9b). The result of this
analysis is a table where each column corresponds to different internal states and
each row specifies the states in one frame of the movie. Thus, this table defines a
behaviour as a sequence of command state transitions (Ayers 2000a).

Ongoing behaviour is comprised a sequence of actions, maintained on an event
stack (figure 9d). Each of these action components, in turn consist of a behavioural
command and associated intensity and timing parameters. The action components
are pushed to the stack, of the order of time, by releaser objects. These releaser
objects are triggered by specific messages from sensor inputs on the robot. The
primary advantage of this arrangement is that compatible action patterns can be
superimposed and the layers corresponding to different task groups can be managed
in parallel as occurs in lobster command systems (Davis & Kennedy 1972). When
the behaviour is released, a releaser (i) saves the current state of the system, (ii)
queues the times of parametric modulation events, and (iii) queues the times of
commands and transitions, and then returns to the event loop to pop transitions off
the queue. A releaser can thus activate multiple action components in parallel,
orchestrating a hybrid behavioural act.

An example of such a behavioural sequence is rheotaxic behaviour or orientation
and compensation for flow or surge (figure 9e). During response to surge sensed by
flow sensors, the controller first lowers the body, depresses the claws and orients
into the current (figure 9e). It then reduces the depression in anterior segments that
will pitch the hull forward and elevates the tail. A set of such behavioural sequences
constitutes the behavioural set of the robot. Each of the behaviours is associated
with a releaser or specific sensory input that triggers the behaviour (see below).

In many cases, behavioural acts, which operate in parallel, superimpose upon
each other at the level of the effectors (Frye & Dickinson 2004). In other cases,
especially when presented with the releasers for two incompatible behavioural
acts, the animal typically chooses to perform one act over the other and one
behavioural act suppresses the other. In our controller, suppressor objects
triggered by releasers mediate behavioural choice. These objects embody lateral
inhibitory connections between commands and are the locus of implementation
of behavioural choice (Kovac & Davis 1980; Edwards 1991). Suppressor objects
for a particular behavioural act maintain a lookup table of action components
that the act suppresses and then clear incompatible action components from the
event stack as the behaviour is released.

9. Tactile navigation

Lobsters must adapt to changing flow and surge. During locomotion, lobsters
operate in still water, relatively unidirectional tidal flows or wave surge
(Martinez 2001). Surging water changes direction with periods of the order of
tens of seconds (figure 10a). Surging water creates problems for stability in the pitch and roll planes as well as in the maintenance of traction with the substrate. Since lobsters are generally active in the dark, they have to rely on flow and contact sensors to detect environmental perturbations (Wilkens et al. 1996), a process we call tactile navigation.

The lobster robot uses antennal sensors that embody labelled line coding to detect flow and contact (Bullock et al. 1977). Each antenna is represented internally by a byte, each bit of which codes for different degrees of antennal bending or buckling (figure 10b). During the operation, the sensor boards are polled for input and the board returns 2 bytes representing the state of the two antennae. We realize selective attention by varying the polling rate for different sensors. Therefore, as inputs from a particular modality become critical, the sensor interface focuses on that modality. How the antennae are used to mediate rheotaxis is described below under electronic neurons (ENs).

Figure 10. Sensors for adaptation to surge. (a) Characteristics of the wave surge seen in wave swept environments (Martinez 2001). (b) Coding in the antennular sensor. The analogue signal from a strain gauge is quantized into seven degrees of bending, each of which corresponds to a bit in the antennal byte. The 8-bit codes for buckling, which is detected by a left–right bend within 150 ms. Buckling is caused by head on collisions of the antenna. A motor drive moves the antenna into different positions. When held forward (c), the antennae are responsive to lateral surge. When held laterally (d) they are responsive to axial surge along the body.
Studies using a lobster-mounted camera allow us to observe interactions of moving lobsters with environmental obstacles. Lobsters often collide with rocks with their antennae and claws. If a collision occurs with just one claw, the response is to make a yawing turn away from the collision. This implies that the lobsters are using their claws as bump sensors. The chelipeds are innervated by a variety of joint receptors that would be activated by collision (Laverack 1976).

We use an analogue accelerometer as a basis for a bump detector (figure 11a). The combination of the bump sensors and the antennal-based collision sense gives the vehicle basic decision-making capability for tactile navigation. If the vehicle collides with an object with its antennae, it will be necessary to circumnavigate the obstacle. If it hits an obstacle with its claws, but not by its antennae, it can probably climb over the obstacle. If it does not hit the obstacle with either, it can probably just walk over the obstacle.

10. Electronic nervous systems

For a deterministic program to control adaptive robotic behaviour, it must be preprogrammed to anticipate all environmental contingencies. In contrast, the innate behaviour of animals emerges from the properties and connectivity of intrinsic neuronal networks (Delcomyn 1980). For robots to achieve the adaptive capabilities of animals, they need to be extended to neuronal control schemes. In particular, neuronal network-based controllers allow flexibility and robustness unavailable to deterministic programs (Abarbanel & Rabinovich 2001). We have been evaluating two different types of neuronal-based controllers for application to the lobster robot, ENs (Pinto et al. 2000) and discrete time map-based neurons (Rulkov 2002).
UCSD ENs are based on a dynamical model of lobster neurons formalized by the Hindmarsh & Rose (1984) equations. The neurons are analogue computers that solve the equations in real time. They can be configured to emulate different types of neurons by adjusting trim pots that specify coefficients of the equations.

UCSD electronic synapses emulate chemical synapses and can be configured to different postsynaptic reversal potentials and time constants. We have instantiated a circuit (figure 4a) with UCSD ENs and synapses to generate walking motor patterns (figure 12). This involved developing a presynaptic inhibitory circuit. The application of a bias current to the neuronal oscillator activated all neurons except the commands. When the commands were activated, the motor programs for forward and backward walking were selected. Using a simple comparator/power FET interface, we were able to interface this EN CPG to one of the lobster robot’s legs. A movie of the EN CPG circuit causing the leg to walk in different directions as in figure 12 is available online2.

EN CPGs can be perturbed and entrained by synaptic input to mediate gait coordination as well as phase- and amplitude-modulating reflexes.

To be useful for robotic control, component-based ENs need to be reduced to analogue VLSI and we have been successful in getting subthreshold VLSI simulations of UCSD ENs to generate excellent replicas of lobster neuron behaviour (Lee et al. 2004). These studies have involved development of ENs, electronic chemical synapses, presynaptic inhibition and the simulation of complex motor programs.

2http://www.neurotechnology.neu.edu/EN_CPGWalking.html.
The generation of walking motor programs is only one aspect of the control of the robot. A more critical aspect of control is at the level of exteroceptive reflexes. The exteroceptive reflexes act on multiple task groups to modulate the behaviour of the whole organism. In invertebrates, the brain is the locus of integration of exteroceptive inputs to activate descending commands (Sandeman et al. 1992). At the level of innate behaviour, the brain mediates layered exteroceptive sensory-motor reflexes to control processes such as taxes, tactile navigation, righting and rheotaxis (Kennedy & Davis 1977).

Instantiation of the circuitry for the adaptive control of complex exteroceptive reflexes in analogue VLSI ENs is presently unattractive for two reasons. First, the circuits require large numbers of neurons and large expensive dies. Second, these reflexes are going to require a lot of annealing; hence there is a need for interactive programming. Discrete time map-based neurons provide an attractive alternative for implementation of the complex circuitry necessary for the control of adaptive behaviour by a robotic brain (Rulkov 2002). The map-based neurons are available for rapid prototyping in the LabVIEW (National Instruments, Austin, TX) environment³.

We have used map-based neurons and synapses to simulate the antennal mediation of flow reflexes in the lobster robot (Ayers & Rulkov 2006). Rheotaxic behaviour in lobsters has two components. The first occurs in response to lateral surge and involves turning into the flow by walking forward on one side and backward on the upstream side. With the antennae held forward (figure 10c), such lateral surge from the left would cause medial bending of the upstream antenna and lateral bending of the downstream antenna. The resulting input is then processed by a neuronal network (figure 13a) to mediate rheotaxis. A pair of bilateral rheotaxic interneurons receives inputs from the highest threshold medial bend element of the same side and the highest threshold lateral bend element of the contralateral side. The output of this neuron is to activate the backward command on the same side and the forward command on the opposite side. This reflex response is demonstrated in LabVIEW simulation in figure 13b.

The second component of rheotaxis is gradual yawing into the flow in result from asymmetric flow along the long body axis. The rheotaxic interneurons in figure 13a would also command the antennae to move to the lateral position (not shown). As the vehicle orients into the flow, the upstream antenna would bend more than the downstream antenna. The medial lower threshold afferents project to a surge interneuron on the same side, while the lateral afferents project to a surge interneuron on the opposite side. The surge interneurons activate the forward command on both sides. In asymmetric surging flow along the long body axis, this arrangement would cause the vehicle to oppose and yaw into the flow when coming from front to rear, and run with and yaw into the flow when coming from rear to front. This reflex response is demonstrated in figure 13c.

The combination of EN CPGs and discrete time map-based neuron brains provides a feasible neuronal network-based controller for biomimetic robots such as the lobster robot (figure 1). The brain could be implemented on a small microcontroller and by the use of D/A converters to convert the command signals (figure 13b,c) to analogue voltages that modulate the EN CPGs (figure 12).

³ http://inls.ucsd.edu/~rulkov/demo/neuron/map/ndemo.html.

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and an integrated CNS could be realized. The primary advantage of EN-based controllers is that they can incorporate chaotic organizational principles. We hold that the use of chaos in controllers will allow the adaptability of robots unfeasible with deterministic programming (Rabinovich & Abarbanel 1998). As both invertebrate and vertebrate locomotor systems are organized by common principles (Stein 1978; Pearson 1993), it would appear that this neurotechnology might have applications both to robotics and neuroprosthetics (Selverston et al. 2004).

Figure 13. Simulation of rheotaxic behaviour mediated by antennae using discrete time map-based neurons. (a) The neuronal circuit. Range-fractionating sensory afferents project to rheotaxic and surge interneurons. The highest threshold bending afferents project to the rheotaxic interneurons. The low and medium threshold bending afferents project to the surge interneurons. (b) Rheotaxic (turning) response to lateral surge when the antennae are deployed forward as in figure 10c. The two panels represent the activity on the neurons in figure 13a when the surge (top two panels) oscillates from left to right to left with a long period. (c) Yawing responses to off centre axial surge (from the right forward quadrant) when the antennae are deployed laterally as in figure 10d. Note the difference in amplitude of the antennal movements (downstream antenna bends less) and the resulting asymmetry in output.

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