Lamprey Robots[1][2]

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Abstract
We have developed a biologically based underwater, autonomous vehicle modeled after a simple vertebrate, the sea lamprey. The robot consists of a cylindrical Plexiglas electronics bay with a polyurethane undulator actuated by shape memory alloy artificial muscles. Sensors include a compass, pitch and roll inclinometers and sonar rangers, the signals of which are quantized into a labeled line code. Behavioral parameters are reverse engineered from the behavior of the target organisms.

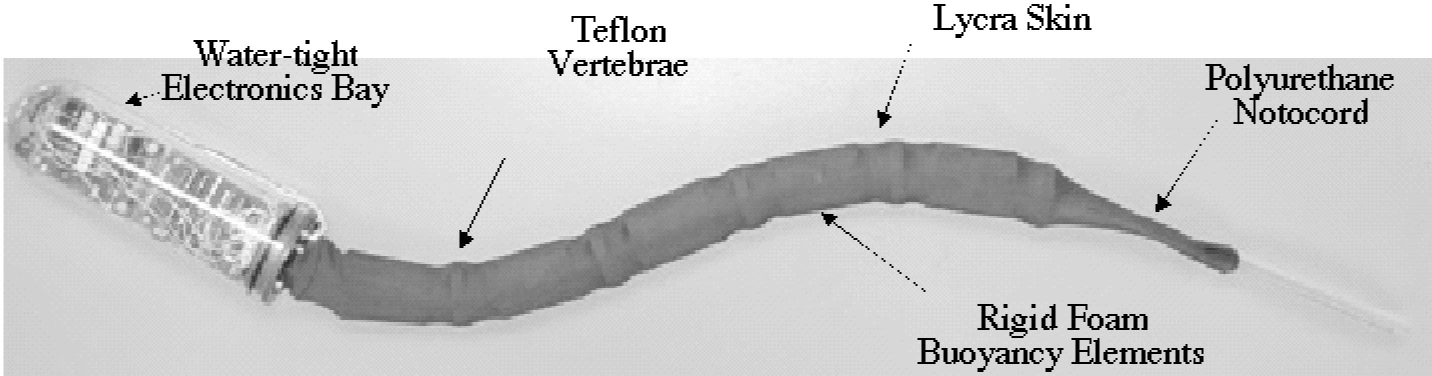

Fig. 1 Lamprey Robot Prototype

Introduction

We have implemented a lamprey-based robot based on biomimetic neurotechnology (Fig. 1). Lamprey swim by rhythmic lateral undulations of the body axis. The propagating lateral axial undulations increase in amplitude from nose to tail. Similar waves travelling from tail to nose can propel the lamprey backward (Ayers, 1989). Rhythmic propagating muscle activity alternating on either side of the body axis underlies this propulsive wave. Lamprey swimming is uncomplicated by pectoral, pelvic, or anal fins. Endurance rather than high speed is characteristic of Anguillform swimming.

Kinematics of Swimming

To quantitatively analyze the undulatory behavior of the lamprey, we employed a computer program (Ayers et al., 1983) uses stop-frame analysis of video images to establish the dynamics of body flexion's (Fig. 2). Filmed sequences of swimming were then digitized and analyzed on a frame-by-frame basis (Ayers, 1989). Kinematic analysis of body curvature demonstrates swimming behavior is organized into lateral flexion waves that propagate either from nose to tail or tail to nose. During swimming, the propagation time of flexion waves down the body axis is equal to the period so specimens always maintain an S-shape during swimming.

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[2] Ayers, J., Wilbur, C., Olcott, C. (2000) Lamprey Robots. In: Proceedings of the International Symposium on Aqua Biomechanisms. T. Wu and N, Kato, [eds]. Tokai University.

Variations in period and curvature of flexion differentiate lamprey behavior acts (Table I. Ayers, 1989).

Thrust occurs when a propulsive wave travels backward over the body at a velocity greater than the speed of forward swimming. Kinematic analysis demonstrates lamprey generate a peak of thrust as each flexion wave passes the cloaca (Fig. 2d-e). The thrust peaks at approximately sixty percent of the body and there are two peaks of thrust for every swimming cycle.

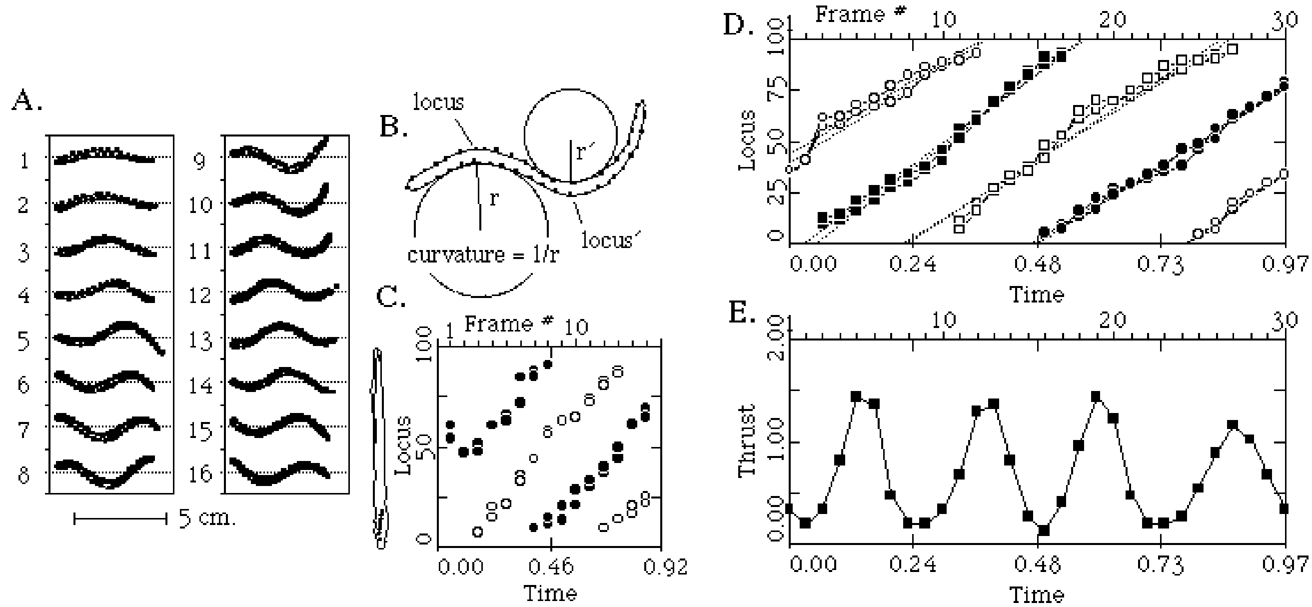


Fig. 2. Kinematic Analysis of Swimming (A). Images of the lamprey body axis as digitized from sequential frames of a movie

We evaluated how swimming movements are effected by hydrodynamic load by analyzing high frequency forward swimming of the lamprey in a wet shallow pan. The analysis demonstrates the active segments during swimming are located in the middle two thirds of the body (curvature vs locus), the mid-region of the body constitutes the propulsor for locomotion, and a passive role for the tail. As a result, our vehicle has three separate functional sections: head, body axis and tail.

Neuronal-circuit based Controller

We adapted a command neuron, coordinating neuron, central pattern generator based controller originally developed as a controller for a lobster robot (Ayers and Crisman, 1992, Jalbert et al. 1995) as the controller for the undulator. The controllers generates control signals for each of 5 body segments which alternate on the two sides and propagate down the body axis such that the propagation time is equal to the period of the undulation (Fig. 2). Modulation of the amplitude and timing of these propagating waves generates the complete behavioral repertoire (Table I).

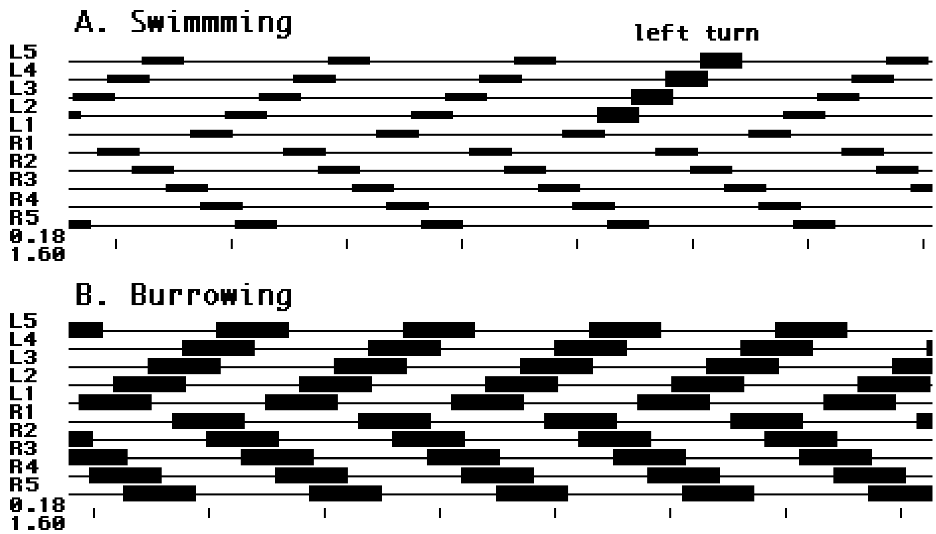


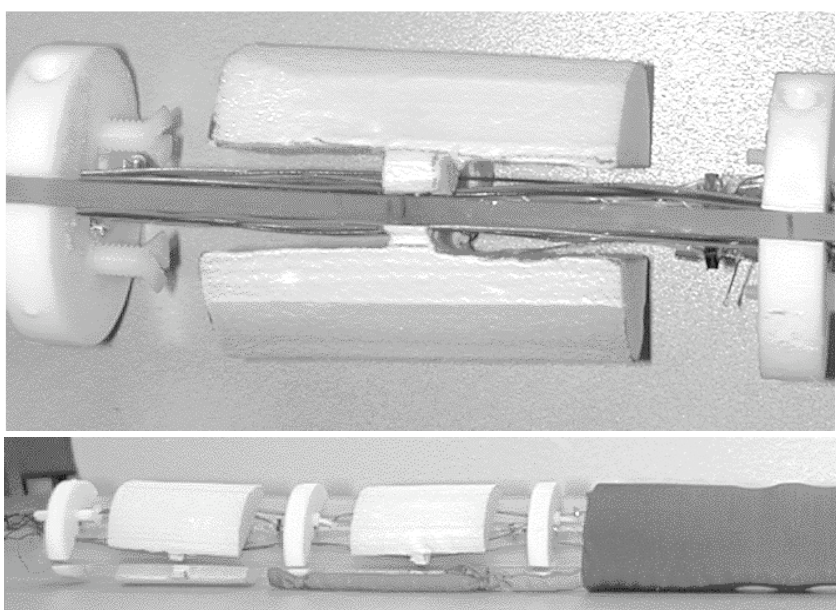
Fig.3.Motor patterns for swimming (A) and Burrowing (B). The width of the bars indicates the recruitment level. When the bar width is increased, a longer pulse is employed to actuate the muscle modules. A left turn is shown in A.

Vehicle

The undulatory vehicle is functionally a three component system consisting of a rigid hull/electronics bay (~15% of the total body length), a flexible body axis supporting the nitinol actuators (~60% of the total body length), and a thin, flexible, passive tail (~25% of the total body length).

Hull: The watertight Plexiglas cylindrical hull houses the electronics (Fig. 5) toward the head, 50% of body mass is located in anterior 39% of body. Watertight through-hull fittings allow for communication between the actuators and electronic interfaces.

A.



B.

Fig. 4. Buoyancy and ballast elements

Axial Beam: The polyurethane body axis supports six Teflon™ vertebrae that attach and pin the SMA actuators along the midline (Fig. 4a). This arrangement transfers force to the flexible backbone causing it to flex laterally. Each of the ten-nitinol actuators is attached at three points on the notochord to minimize any offset distance from the polyurethane and to control shape changes. Buoyancy elements of close-cell foam are placed between the vertebrae, but are offset from the notochord so as not to impede bending of the polyurethane (Fig. 4a). These units also help maintain a uniform cylindrical body form. Lead shot weights encased in latex are placed parallel to and below the polyurethane but within the skin to keep the vehicle submerged and to maintain a dorsal side-up orientation (Fig. 4b). Lycra ™ covers the body axis acting as a skin attached posterior to the hull, continuing the length of the notochord, and terminating between the fins of the tail. Lycra ™ allows water to penetrate, effectively cooling the actuators but protecting them from any detritus in the water column.

Tail: The tail, contiguous from the notochord, is tapered polyurethane overlain by fiberglass shimstock. The shimstock is shaped to mimic the corresponding lamprey dorsal fins, the rostral fin being much larger than the caudal. This arrangement allows for an increase in axial stiffness (shimstock has a higher Young's modulus) while maintaining the same bending stiffness thus reducing energy loss in the tail region and inducing the undulatory wave to increase in amplitude as it progresses from head to tail.

Actuators: The vehicle is propelled by ten nitinol actuators which consist of a watertight assembly of 0.01″ nitinol, etched PTFE™ tubing, stainless steel crimps, 32 AWG lead wire, Kevlar™ ligaments and Aquaseal™ sealant (Witting et al., 2000). Operation under water allows fast convective cooling necessary for the nitinol martensite transition. Watertight actuators are necessary for fast response time from the nitinol. The rate of the martensite transformation determines the maximum alternating frequency of the actuators (Witting, et al., 2000).

The SMA actuators are controlled by neural-based circuit software that activates the actuators in a characteristic bursting pattern (Fig. 3) and control the amplitude of contractions via pulse width modulation (Witting et al, 2000). During operation the amplitude of the control signals is inversely proportional to the period of undulations

System Integration

A serial I/O interface links the processor to the sensor and actuator interfaces. These interfaces consist of three boards: A serial/sensor interface (Fig. 5a), a current-driver interface to control the nitinol actuators (Fig. 5b) and an analog sensor board that supports a compass and pitch and roll inclinometers and quantizes these signals to bit representations. This allows us to use a laptop computer during development and to switch to a small, embedded microcontroller for autonomous operations. Each of the sensor elements is a switch and each switch is mapped to the bit of a shift register that the computer reads via a serial line. When a state change occurs in the motor pattern generating circuit, it writes, via a serial line, to a series of shift registers each bit of which is mapped onto the current driver and then to a given actuator (Fig. 5). This basic architecture is shared with the lobster-based robot (Ayers et al., *this volume*).

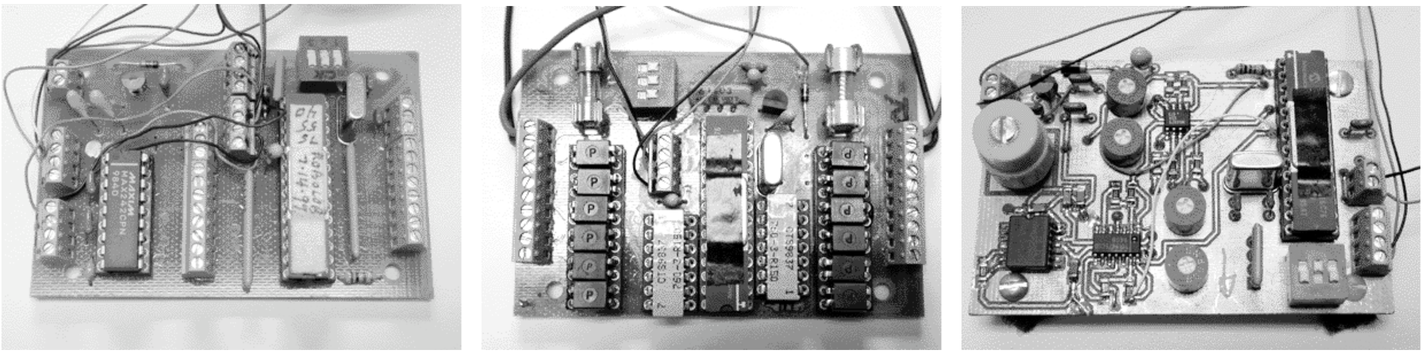


Fig. 5 Undulator Interface Board Set (A). Serial/Sensor Interface Board. (B). Current driver board for nitinol actuators. (C). Analog sensor board containing compass and pitch and roll inclinometers.

Behvioral Libraries

A behavioral library of the lamprey has been developed by reverse-engineering sequences of lamprey behavior. This library consists of a table of timing parameters derived from the quantitative analysis of the various forms of behavior such as swimming, crawling, burrowing, withdrawal, and turning (table I). A look-up table generated from the behavioral library forms the basis for the dynamics of the controller of the vehicle

Behavior	Period (sec)	Phase	Curvature
Slow swim	3.17	0.013	0.4
Average swim	1.90	0.013	0.37
Escape swim	1.52	0.013	0.43
Forward crawl	5.89	0.012	1.27
Backward crawl	10.61	-0.011	0.96
Burrowing	5.66	0.015	0.65

Table I. Timing and curvature parameters of different lamprey behavioral acts. Period was normalized to a 1 meter vehicle based on extrapolation from measurements of period as a function of length for smaller lamprey. Phase is the intersegmental delay/period based on a 110 segment lamprey. Adapted from Ayers, 1989.

Autonomous Behavior

The overlying motivation of the vehicle in operation will be to swim on a search segment on arbitrary heading using the on-board compass. A sonar altimeter will allow the vehicle to swim at and altitude characteristic of objects of interest and look forward sonar will scan in front of the vehicle due to the ongoing axial undulations. Different sensors will define releasers for different behavioral sequences (withdrawal, turning, pitch and roll modulation, etc) which are defined by characteristic undulation parameters (Table I). Releasers will be defined by "byte masking" the sensor bits maps. This releaser library associated exteroceptive reflexes (Ayers, 2000) will form the basis of the reactive navigational capabilities of the vehicle. Most behavioral acts involve sequences of these fundamental action patterns (Table I) and we are expanding the library of sequences to include compensation for current and surge, locomotion in collisions, disturbances of primary orientation, navigation and searching.

Sensory feedback will be used to elicit behavioral switches in response to environmental perturbations. For example, the robot will need to increase its swim speed when it encounters strong currents, turn away from or into objects of interest, and dive and climb according to static pressure/altitude changes to maintain a constant depth in the water column. In addition, the system will face numerous situations where they are presented simultaneously with the sensory releasers for incompatible behavior (e.g. beacon tracking vs. surge compensation). We use modulation of commands as the basis of choice (Ayers, 2000). A behavior choice hierarchy based on a truth table of releaser combinations formalizes the behavioral hierarchy.

Conclusions

It is feasible to adapt a modular architecture originally developed for an ambulatory robot (Ayers, this volume) to an undulatory robot. This conservative architecture may therefore form the basis of a variety of biomimetic robots adapted to any niche where animal models exist.

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