Northeastern University

Conference Program

Neurotechnology for Biomimetic Robots

Marine Science Center

Northeastern University
East Point,
Nahant, MA 01908

May 14-16, 2000

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Theme of Conference.

Animals have evolved to occupy every environment where one might wish to operate a robot, save outer space. In most cases animal performance transcends the efficiency and agility possible with current engineering solutions. Until recently, there were few examples of actuators that might permit the linear actuation characteristic of animal systems. Moreover advances in transducers and MEMs technology now permit sensors which code environmental information in the same fashion as animal sensors. Combined with new methods of computational network modeling, these advances have permitted development of a new class of truly biomimetic robots. Swimming robots achieve propulsion by whole body undulations or tail flapping. Walking robots use multiple jointed legs to mediate locomotion. Inroads are even being made in flying robots which locomote by flapping wings.

These robotic systems represent the forefront of neurotechnology that implements engineering solutions through the application of biological control and transducer principles. This neurotechnology affords the opportunity to produce truly reactive autonomous robots. Studies of animal behavior have extended these capabilities to reactive navigation and investigation. The integration of these higher order animal control schemes with biomimetic sensors and actuators may revolutionize robotics.

Program Sponsors

DARPA / DSO Controlled Biological Systems Program
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Program

Neurotechnology

Biomimetic Sensors
Nick McGruer (NU) Paul Zavracky (Microoptical Corp): Biomimetic MEMs Sensors
Reid Harrison (CalTech) Fly-Inspired VLSI Vision Sensors
John Kauer (Tufts): Electronic Noses
Nicolas Franceschini (CNRS Marseilles): Optical flow Sensors
Oliver Landolt (Cal Tech) Moving Eye Sensors
Biomimetic Actuators
Jan Witting (NU): SMA Actuators
Roy Kornbluh (SRI) Electroactive Polymer Artificial Muscle
Bob Horning (Honeywell) Electrostatic MEMs Actuators
Michael Goldfarb (Vanderbilt) Piezoelectric actuators
Biomimetic Control Architectures
David Barrett (IS Robotics): Evolved Control Architectures
Simon Giszter (MCPH)Biomechanical primitives and hierarchy
Joseph Ayers (NU): A Conservative Biomimietic Control Architecture

Vehicles

Undulatory and Swimming Robots
Gavin Miller (SnakeRobots.com.) Snake Robots
Cricket Wilbur (NU), Scott Currie (UCR), Bill Vorus (UNO): Anguillform Propulsion
Jamie Anderson (Draper Labs): Robotic Tuna
Motomu Nakashima (Tokyo Institute of Technology) Robotic Dolphin
Naomi Kato (Tokai University) Pectoral fin controllers
Ambulatory Robots
Dan Koditschek(U. Mich.), Bob Full (UC Berkeley): Computational Neuromechanics
Holk Cruse (Bielefeld): Insect Based Robots
Roger Quinn / Roy Ritzmann (Case Western) Robotic Cockroach
Frank Kirchner (GMD: Bonn): Robot Scorpion
Flying Robots
Gernot Wendler (Köln): Computer Control of an Insect Flight Motor
Ron Fearing (UC Berkeley)A Micromechanical Flying Insect
Robert Michelson (Georgia Tech) Entomopter

Autonomous Behavior

Ralf Möller (U. Zurich) Visual Homing
Barbara Webb (Stirling University): Cricket based phonotaxic robot
Frank Grasso (MBL): Chemosensory tracking
Mark Willis (U. Ariz.) Odor Guided Navigation
Owen Holland (Bristol): Predatory Robots
Michael Dickinson (UC Berkeley)Sensory control and aerodynamics of maneuverability and target search
Mandayam Srinivasan (Canberra): Visual Control of Bee Navigation and Homing

Agenda

Sunday, May 14

Lunch: 12:00

Neurotechnology

Biomimetic Sensors
Session Chair: Holk Cruse

1:00 PM	Nick McGruer, Paul Zavracky	NU & Microoptical Corp	Biomimetic MEMs Sensors
1:30 PM	Reid Harrison	CalTech	Fly-Inspired VLSI Vision Sensors
2:00 PM	Nicolas Franceschini	CNRS Marseilles	Optical flow Sensors
2:30 PM	Oliver Landolt	Cal Tech	Moving Eye Sensors
3:00 PM	BREAK		

Biomimetic Actuators
Session Chair: Paul Zavracky

3:30 PM	Jan Witting	NU	SMA Actuators
4:00 PM	Roy Kornbluh	SRI	Electroactive Polymer Artificial Muscle
4:30 PM	Bob Horning	Honeywell	Electrostatic MEMs Actuators
5:00 AM	Michael Goldfarb	Vanderbilt	Piezoelectric actuators

Dinner: 6:30

Monday, May 15

Biomimetic Control Architectures
Session Chair: Barbara Webb

9:00 AM	David Barrett	IS Robotics	Evolved Control Architectures
9:30 AM	Simon Giszter	MCPH	Biomechanical primitives and hierarchy
10:00 AM	Joseph Ayers	NU	A Conservative Biomimietic Control Architecture
10:30 AM	**BREAK**		
11:00 AM	John Kauer	Tufts	Electronic Noses

Vehicles

Undulatory and Swimming Robots
Session Chair: Mike Dickinson

11:30 AM	Gavin Miller	SnakeRobots.com	Snake Robots
12:00	**Lunch**		
1:00 PM	Cricket Wilbur, Scott Currie, Bill Vorus	NU, UCR, UNO	Anguillform Propulsion
1:30 PM	Jamie Anderson	Draper Labs	Robotic Tuna
2:00 PM	Motomu Nakashima	Tokyo Institute of Technology	Robotic Dolphin
2:30 PM	**BREAK**		
3:00 PM	Naomi Kato	Tokai University	Pectoral fin controllers

Ambulatory Robots
Session Chair: John Kauer

3:30 PM	Dan Koditschek	U. Mich	Stabilization of Mechanical Oscillators By Feedforward Clocks
4:00 PM	Holk Cruse	Bielefeld	Insect inspired neural network for the control of robot walking
4:30 PM	Roger Quinn / Roy Ritzmann	Case Western	Robotic Cockroach
5:00 PM	Frank Kirchner	NU, GMD: Bonn	Robot Scorpion
6:30	**Dinner:**		

Tuesday, May 16

Flying Robots:
Session Chair: Roy Ritzman

9:00 AM	Gernot Wendler	Köln	Computer Control of an Insect Flight Motor
9:45 AM	Ron Fearing	UC Berkeley	A Micromechanical Flying Insect
10:15 AM	Robert Michelson	Georgia Tech	Entomopter

10:45 AM **BREAK**

Autonomous Behavior

Autonomous Behavior I
Session Chair: Gernot Wendler

11:00 AM	Ralf Möller	U. Zurich	Visual Homing
11:30 AM	Barbara Webb	Stirling University	Cricket based phonotaxic robot

Lunch: 12:00

1:00 PM	Frank Grasso	MBL	Chemosensory tracking
1:30 PM	Mark Willis	U. Ariz.	Odor Guided Navigation
2:00 PM	Owen Holland	Bristol	Predatory Robots

2:30 PM **BREAK**

Autonomous Behavior II
Session Chair: Nicolas Francischini

3:00 PM	Michael Dickinson	UC Berkeley	Sensory control and aerodynamics of maneuverability and target search
3:30 PM	Srini Srinivasan	Canberra	Visual Control of Bee Navigation and Homing

Abstracts

Jamie Anderson
Charles Stark Draper Laboratory

The Vorticity Control Unmanned Undersea Vehicle--An Autonomous Robotic Tuna

The Vorticity Control Unmanned Undersea Vehicle (VCUUV) at Draper Laboratory is the first mission-scale, autonomous underwater vehicle which uses vorticity control propulsion and maneuvering. The VCUUV is a self-contained, free swimming research vehicle that follows the morphology and swimming motion of a yellowfin tuna. A rigid pressure hull comprises the forward half of the vehicle which houses batteries, electronics, ballast and hydraulic power unit. The aft section is a freely flooded articulated robot tail with is terminated with a lunate caudal fin. Utilizing tail kinematic data obtained with the MIT Robotuna apparatus, the VCUUV has demonstrated stable autonomous swimming up to 2.4 knots and aggressive maneuvering trajectories with turning rates up to 75 degrees per second.

Joseph Ayers
Northeastern University, Marine Science Center
A Conservative Biomimietic Control Architecture

The controller for our robots is organized at two levels. At the lowest level a pattern generating circuit generates the pattern which controls individual legs in the ambulator or segments of the body axis in the undulator. At the highest level the controller is organized around the behavioral libraries and a reactive 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 state sequences specified by the behavioral libraries.

We derive behavioral libraries from reverse animation of the behavior of the model organisms. The biological assumption of this analysis is that the posture and action of the different task groups is specified by a set of command neurons that command the task group to generate a different state. Thus the task of this analysis is to specify the state of the task groups in each of the frames of a movie. For example, we have found that the ongoing state of a lobster can be defined by 11 task groups that can exist in 2 to 5 different states. During analysis of video sequences, a panel of buttons is used to specify the states of the different groups in each of the frames of a movie. These state change sequences constitute the behavioral library of the vehicles.

The sequence of commands that underlie ongoing behavior is maintained on an event stack Action components are pushed on this stack in order of time by releaser objects. Releaser objects are triggered by different methods of sensor objects that indicate orientational and magnitude components. Sensor objects receive input from an array of MEMs sensor switches and activate different releasers depending on the character and receptive field of the sensors activated by exteroceptive input. Suppressor objects, triggered by releasers embody lateral inhibitory connections between commands and are the locus of implementation of behavioral choice.

The sequences of state changes specified in the behavior libraries can be modulated in intensity. In animal models, this modulation would be mediated by circulating neuromodulators. In our controller the intensity of behavioral acts is controlled by the temporal compression used to place them on the queue as well as by variations in the the pulse widths associated with different recruitment levels which will modulate the amplitude of the muscular contractions. We use ipsilateral and contralateral biases from sensor input to mediate yaw plane modulation During operation, the vehicle will be given an underlying motivation (i.e. home on a sonar beacon or initiate a search on an arbitrary compass heading). During execution of this motivated task, the controller will respond to environmental contingencies specified by its sensor suite by evoking pre-programmed sequences from its behavioral library.

Supported by DARPA / DSO through ONR Grant N00014-98-1-0381

David Barrett
IS Robotics
Evolved Control Architectures:

Biologically inspired robotics for entertainment applications often include very large numbers of actuators, heavily coupled skeleton structures and complex non-quantifiable performance parameters. Developing a satisfactory control architecture for such systems is currently both extremely time-consuming and potentially hazardous.

One method of dramatically decreasing the development time is to continue to follow the biological analogy and develop a control architecture that can evolve to an acceptable level of performance.

Determining the optimal motion for any flexible skinned robotic character is an acutely complex problem involving the robot's skeletal kinematics and body/skin dynamics. The overall intractability of the dynamics of a flexible body precludes a purely analytical solution. The immense size of the experimental variable space prevents a purely empirical one. In order to overcome both difficulties, we have developed a self-optimizing motion controller based on a genetic algorithm. This controller effectively uses evolutionary principles to exponentially optimize system performance.

Holk Cruse
Universitat Bielefeld
Insect inspired neural network for the control of robot walking

Control of walking has to deal with two problems: the coordination between legs and the control of the movement of the individual leg. A number of local rules suffice for the emergence of different gaits as are tripod or tetrapod gait or the recovery from disturbances or the start from different leg configurations. The quasi-rhythmic movements of a single leg are controlled by a modular system. The stance net is extremely simplified by application of a combination of negative and positive feedback at joint level. This simplification is possible because the loop through the world is exploited instead of an explicit calculation of stance trajectories. Control of swing movement, although at first glance the simpler task, requires a somewhat more complex, but still simple controller net. We can show that the switch from swing to stance depends on sensory input, ground contact, and on an internal state which may be termed "swing motivation". This internal state in turn depends on geometrical values, namely the distance between two neighboring legs.

Michael Dickinson
UC Berkeley
Sensory control and aerodynamics of maneuverability and target search

A central feature in the natural history and behavior of flies is the ability to find rare food recourses. While the fly uses many sensory modalities as part of its flight control system, vision and olfaction are essential for the search and recognition of small and widely dispersed targets. We are currently attempting to determine the means by which the fly's nervous system integrates visual and olfactory input to appropriately modify motor output. By tracking freely flying flies within a large arena it is possible to reconstruct what a fly sees as it moves through a structured visual landscape. The flight paths of fruit flies consist of straight sequences interspersed with rapid saccadic turns, during which the animal changes its heading. While the temporal and spatial distribution of saccades may appear quite stochastic, after reconstructing the visual input it is possible to link nearly every saccade turn to a point when the rate of expansion within one visual field passed a critical threshold. After each saccade, flies attempt to stabilize sharp contrast edges resulting in the straight flight sequences. As they approach an object, however, the asymmetrically looming edge elicits first a decrease in forward velocity and then a rapid collision-avoidance saccade. The net result is that animals fly slowly and saccade frequently within dense clusters of objects, whereas they fly rapidly and saccade less frequently within open landscapes. Chemical odors appear to influence flight behavior, not by overriding optomotor control, but rather by altering the gains and thresholds of visual control circuits. This clever fusion of olfactory and visual information produces a robust and efficient search algorithm and should serve as a useful model for control systems in autonomous vehicles.

Ron Fearing
UC Berkeley
A Micromechanical Flying Insect

The goal of this 5-year ONR MURI/DARPA supported project is to design a 25 mm wing span micromechanical flying insect (MFI) based on the aerodynamics of fruit flies and blowflies. We developed a thorax structure using four bar frames combined with an extensible fan-fold wing to provide adequate wing stroke and rotation. Calculations using a simple resonant mechanical circuit model show that piezoelectric actuators can generate sufficient power, force, and stroke to drive the wings at 150 Hz. A manufacturing process using laser cut stainless steel and folding has been developed to construct a thorax model at 30% larger than final size. 90 degrees wing stroke has been demonstrated using PZT actuators, and 150 degrees wing stroke is expected using single crystal PZN-PT materials.

Nicolas Franceschini
C.N.R.S., Neurocybernetics Research Group, Marseilles
From Fly Vision To Robot Vision

Flies are miniature seeing creatures that use a host of smart sensors for immediate action upon the steering. They navigate swiftly in the most unpredictable environments, avoiding obstacles without resorting to any sonars or laser range-finders. They process their sensory signals on-board without being tethered to a supercomputer. A fly is equipped with " only " about 1 million neurons and it views the world with no more than 6000 pixels. And yet this humble flyer can attain a level of performance beside which present-day mobile robots look quite puny.

We studied the neurobiological principles involved in motion detection using a technique of single neuron recording combined with optical microstimulations of single photoreceptor cells on the retinal mosaic (rev.1). In this way we attained the functional diagram of an Elementary Motion Detector (EMD), from which we derived a miniature analog electronic circuit for sensing directional motion. We then conceived a robot that would sense the optic flow field on the basis of such biology-derived EMD's and guide itself visually. This Robot-Fly (robot-mouche) was equipped with a genuine compound eye and 118 EMD's that would sense the optic flow field in the azimuthal plane and control the steering so as to avoid obstacles while the (12 kg) robot was running at a relatively high speed (50cm/s. Simulation studies showed that such a robot can automatically adjusts its speed to the density of obstacles present in the environment, because the radius of vision appears to be proportional to speed. Further studies showed that the same principles of motion detection can be used to guide a flying robot, have it follow a rough terrain and land automatically. Experimental validation is under way using a laboratory built helicopter system (with collective pitch but without a swashplate) equipped with a camera eye, fly EMD's, and an inertial system. The whole rotorcraft (0.8 kg), which is mounted on to the tip of a whirling arm, has only 3 degrees of freedom and reaches speeds up to 6 m/s.

In two other projects, we studied the benefits of a controlled microscanning, like the one we recently discovered in flies using single unit recording on the behaving animal. One of the principles inspired by our biological findings was implemented onto a 0,7 kg wheeled robot that succeeded in avoiding the (contrasting) walls of an arena in spite of the very low resolution of its eye (24 pixels). The second principle was implemented onto a miniature (0.1 kg) twin-engine, twin-propeller aircraft which, while hanging from a wire attached to the ceiling, can fixate a target and track it regardless of its distance (up to 1.5 m) and contrast (down to 10%). This latter project also exemplifies how two sensory modalities, visual and inertial, can be fused to improve the stability and performances of micro air vehicles - which are difficult to control due to their small mechanical time constants.

The biorobotic approach we followed since 1985 appears to be fruitful in two ways. On the one hand one can glean interesting ideas, opening to novel questions about the utility and working of natural microsystems. On the other hand this approach opens up to the design of autonomous, sensory-motor vehicles and micro vehicles that can capitalize on the million-century experience of biological evolution.

Simon Giszter
MCP Hanneman

Biomechanical Primitives and Hierarchy

Spinal cord modularity of circuitry and function may provide an important simplification of the interface provided to descending controls and may also represent a developmental bootstrap for motor learning. Theoretical analyses show that such a modular scheme may have many advantages (e.g. Mussa-Ivaldi 1997). There is also biological inspiration and support for development of such theoretical schemes (Giszter, Mussa-Ivaldi and Bizzi, 1993).

We have explored modularity in aimed movements during spinal cord reflexes using a number of approaches. Among these are differentiation, mechanical perturbation and direct activation of spindle of golgi tendon mechanosensors in selected muscles, and independent components analysis and cosine packet matching pursuit algorithms to find the lowest dimensional representations of data. All our data support a modular construction of behavior comprised of a central pattern generator or rhythm generator which, in participation with sensory feedback, times a collection of force-field primitives. The primitives have intrinsic dynamics and amplitude controls, which are independent of the CPG. The elements organizing the force-field primitive's behavior consist of premotor drives, feedback systems and intrinsic muscle properties acting as a unit. These primitives form a basis for the flexible construction of movement, in a scheme akin to the templates and anchors recently discussed by Full and Koditschek, 1999.

I will present ICA and cosine packet decomposition of behaviors, together with muscle vibration effects and collision induced perturbations to support our current model of movement construction.

Supported by NIH NS34640.

Michael Goldfarb, Michael Gogola, Gregory Fischer, Vanderbilt University
Ephrahim Garcia, DARPA
The Development of Piezoelectrically-Actuated Robot Insects

This paper describes a minimalist mobile robot design approach that offers a high locomotive efficiency which has been incorporated into the development of a dynamically controlled piezoelectrically actuated mesoscale robot quadruped. The design described utilizes a lightly damped skeletal structure that generates locomotion when vibrationally excited at a skeletal resonance by two piezoelectric unimorph actuators. The skeletal structure consists of four articulated legs used to produce a trot type gait. Each articulated leg moves in two degrees of freedom to create elliptical foot motions that enhance locomotion efficiency and rough surface capability. Directional control is achieved by tuning each leg to a slightly different resonant frequency, so that differential control of leg amplitude can be achieved by modulation of the actuator excitation frequency. Compact power electronics have been developed and self-powered (i.e., battery-powered) operation has been demonstrated. The most sophisticated of the designs that will be presented has a footprint that measures 9 cm x 6.5 cm and weighs 51 grams without the electronics and 104 grams with them. Data is presented that characterizes the average speed and typical power consumption of the robot insect at various excitation frequencies.

Frank W. Grasso

Flow- and Chemo-sense for Robot and Lobster Guidance in Odor Source Tracking

Marine Biological Lab, Boston Univ Marine Program Woods Hole, MA, USA
and Brooklyn College, Psychology Department Brooklyn, NY

The physical processes that distribute fluid-borne chemicals in the natural world make the task of tracking odors to their source a serious challenge for animals that use chemical senses to locate food, mates and other resources. Analysis of the chemo-orientation behavior of American lobsters (Moore Sholz, Lakoomis and Atema, 1991, Basil and Atema 1994, Beglane, Grasso and Atema 1997) indicates that animals trying to locate the source of an odor might use cues derived from the fluid dynamic-processes which govern the spatial and temporal distribution of odor (Moore and Atema 1990, Dittmer, Grasso and Atema 1995,1996).

This complex and chaotic physical system challenges the brain of a plume-tracking animal with complex information processing and sensory-motor integration tasks (Grasso, Basil and Atema 1998). Questions of which sensory cues lobsters use and which strategies are implemented in the lobster brain can be indirectly addressed using appropriately scaled, model-lobsters (i.e., Robolobster: Grasso, Consi, Mountain and Atema 1999 and BICSAAR robots Grasso, Borden and Atema 2000 in prep.). Our strategy has been to run robot-lobsters under identical physical conditions to those experienced by lobsters in earlier experiments. We conducted a series of robot experiments to examine the validity and limitations of the guidance from turbulent structure hypothesis. Performance of lobsters and robots (running putative lobster strategies) were quantitatively compared to evaluate the power of a given guidance hypothesis (or strategy) to explain lobster behavior. The results indicate that while strategies such as pure-chemical tropotaxis, odor-gated rheotaxis or flow-informed chemical tropotaxis are effective in guiding the robot to the source, they are not able to fully explain lobster plume-tracking behavior. We conclude that these animals are using tracking strategies of still greater sophistication.

Supported by: This work is supported by a grant from DARPA and ONR.

Reid Harrison
CalTech
Fly-Inspired VLSI Vision Sensors

Vision is a vitally important sense for flying insects. Over half of the 350,000 neurons in the housefly's brain are believed to have some role in visual processing. Flies use visual motion cues to navigate through turbulent air, avoid obstacles, chase other flies, and land safely. Much is known about the neural circuitry that extracts motion information from retinal light intensity signals. We describe the development and testing of integrated silicon sensors that estimate visual motion using architectures derived from the neurophysiology of the fly optic lobe. We built VLSI systems incorporating light sensors and information processing circuits side by side on the same chip. These continuous-time analog CMOS circuits operate in the weak inversion (subthreshold) regime to match biological time constants and achieve sub-milliwatt power dissipation. Detailed characterization showed our sensor to be an accurate implementation of the Hassenstein-Reichardt motion detector model, originally developed to describe insect visual responses. We developed a novel test paradigm using stimuli with natural image statistics and spatiotemporal noise to evaluate the sensor's robustness. Our sensors were able to discriminate motion direction using naturalistic stimuli in noisy conditions (SNR < 1). The silicon system was tested in the context of a visually guided behavior---the optomotor stabilization response. Direct comparisons with the fly were made in real-time, closed-loop control experiments. Finally, we investigated the issue of sensory fusion and explored a circuit that could assist in the integration of visual motion sensors with other sensors, such as angular rate gyroscopes.

Owen Holland
Intelligent Autonomous Systems Lab, University of the West of England

A robot predator

A truly autonomous mobile agent, whether robot or animal, requires no external assistance in carrying out its mission. A tacit part of every mission is the requirement to stay 'alive' until the mission is completed; as well as avoiding self destruction, staying 'alive' means not running out of energy. Most so-called autonomous robots avoid this problem, usually by carrying sufficient energy to achieve their mission, or by being given energy by regular human intervention; in contrast, animals obtain the energy they need from the environment. This paper describes an ongoing project to build a robot capable of surviving in the wild, just like an animal. The robot will live free on agricultural land, hunting and catching slugs, fermenting them to biogas, and using the biogas to generate the electricity that is its primary power source. As well as presenting a host of engineering problems to be solved, the project has forced us to realise that many aspects of animal foraging and hunting behaviour represent good engineering solutions, and that our robot control systems should therefore take direct inspiration from those of animals.

Robert Horning
Honeywell Technology Center, Plymouth, MN
Polymer-Based MEMS Actuators for Biomimetics

MicroElectroMechanical Systems (MEMS) fabricated in plastic have capabilities not possible in the more traditional MEMS made from silicon. An electrostatic polymer-MEMS actuator will be described. This actuator has micro-scale unit cells configured in a 3-D array to provide macro-scale forces and displacements. The 3-D arrangement of unit cells is reminiscent of biological muscle. Our DARPA-sponsored program is targeting a ~1 cm3 actuator with 3 mm displacement (30% strain). Modeling has shown that nearly an order of magnitude increase in force can be achieved with strains limited to 3-5%, making the device applicable to many biomimetic robots. Improvements in the fabrication and assembly techniques have led to actuators which now are approaching the theoretical predictions. Power requirements are low since the actuator is electrostatic. Reliability has yet to be measured; however, several aspects of both the design and the fundamental mechanism point to the ability to achieve high reliability.

Naomi Kato
Tokai University, Japan
Pectoral Fin Controllers

It is necessary for underwater vehicles to perform precise maneuvering such as hovering and turning at a certain point. The high maneuverability enables the underwater vehicles not only to survey an intricate seabed, but also to perform a dexterous work using multiple manipulators in their floating condition.

Instead of the screw-type thrusters and wings installed in existing underwater vehicles, this study is aimed at examining a new device for maneuvering an underwater vehicle based on observation and experimental analysis of pectoral fin motion of Black Bass.

Fin motion like the beating motion of a bird will generally consist of four fundamental motions: (1) flapping motion in vertical plane, (2) lead-lag motion, which denotes a posterior and anterior motion in the horizontal plane, (3) feathering motion, which denotes a twisting motion of the fin pitch, and (4) spanning motion, which denotes an alternatively extending and contracting motion of the fin span. This study assumes a rigid pectoral fin, neglecting the spanning motion, to develop mechanical pectoral fins.

This presentation summarizes on-going project on mechanical pectoral fin from the following four aspects.

(1) Maneuver of fish robot in horizontal plane with a pair of two-motor-driven mechanical pectoral fins(2MDMPFs) generating the lead-lag motion and the feathering motion,

(2) Control of interaction of forces and moment between an underwater vehicle in a free swimming condition and a manipulator by a pair of 2MDMPFs in horizontal plane,

(3) Development of a pair of three-motor-driven mechanical pectoral fins(3MDMPFs) generating the lead-lag motion, the feathering motion and the flapping motion to apply to an autonomous underwater vehicle with high maneuverability?and experimental and theoretical analysis of hydrodynamic characteristics of 3MDMPF,

(4) Development of an autonomous underwater vehicle equipped with the pair of 3MDMPFs named "BASS III" and its swimming performance.

John S. Kauer and Joel White
Dept. of Neuroscience, Tufts University School of Medicine
An Artificial Olfactory System Based on the Biological Sense of Smell

We are developing an artificial olfactory system for rapid sampling and identification of volatile chemicals in the environment. At present we have incorporated more than 20 different attributes of the biological pathway into the device. The Tufts Medical School Nose (TMSN) presents odor samples to an array of optically-based, cross-reactive chemical sensors via brief negative pressure pulses („sniffing‰) and active feedback mechanisms for optimizing recognition of the spatial/temporal response patterns generated by the sensors. Unknown test odors are identified by comparing sensor signals to a stored set of target signals. As in the biological olfactory system, sensors produce signals with different amplitudes and time courses that are influenced by both presentation of different odors as well as by the parameters used for sampling (e.g., sniff duration, amplifier gain, and various sensor control functions). We will discuss the biological attributes that we have used to design various aspects of this device, describe how we have implemented these attributes in hardware and software, and present the overall design philosophy that includes not only learning from biology to build better engineered devices, but also learning from the engineering process to ask defined questions about biological function.

Supported by NIDCD, ONR, and DARPA.

Frank Kirchner
GMD AIS/BAR and Northeastern University
The Scorpion Robot – Towards Autonomous Real World Systems-

Biological systems solve problems which today's technical systems can't. The biomimetic approach to robotics is the attempt to apply solutions created by evolution to technical systems. This approach is not restricted to mechanics engineering but includes and puts emphasis on the behavior of autonomous systems. We are convinced that the study of animal behavior leads to models and hypotheses that help to create new technical solutions in analogy to their successful counterparts in nature. The long-term goal is to achieve robots that autonomously interact for an unrestricted time with a real world environment and that enhance their level of performance with experience gained from the ongoing interaction with the world.

In our most challenging project, the Scorpion Project, we are working towards this goal by integrating a low level behavioral repertoire with a high level control scheme that learns to identify temporal sequences of low level behaviors that form robust complex behavioral acts.

This talk will focus on the low-level behavior of the system. We will demonstrate how the basic ambulation patterns are designed, organized and implemented. In preliminary experiments on one of our platforms we will demonstrate the robustness of this approach. Video sequences and data derived from the machine during basic ambulation are presented and discussed in light of the next step of this project, which is to integrate these mechanisms with the higher level functional (task oriented) level of control of the system.

Supported by DARPA grant #N00014-99-1-0483)

Haldun Komsuoglu, Eric Klavins, Robert J. Full and Daniel E. Koditschek
University of Michigan and UC Berkeley
Toward the Control of Coordination

In a recently reported set of experiments, a simple compliant leg hexapod robot, RHex, negotiates widely varied and dramatically adversarial terrain at speeds exceeding one body length per second when driven by a two stroke purely feedforward reference "clock." Although the mechanics associated with this behavior are far more complex than can presently be studied analytically, the design and implementation of this robot has been closely inspired by insights into the biomechanics of animal locomotion emerging from a large collaborative project on Computational Neuromechanics. We will review the key notion of an "anchored template" in the specific context of this robot and describe recent progress toward the goal of demonstrating explicitly (both analytically and empirically) how RHex's gait is regulated according to these principles. It is our expectation that continued systematic efforts of this kind to extract the principles of animal locomotion will result in more capable robots as well as novel refutable biological hypotheses.

At the present time a significant gap in our understanding of animal and machine locomotion surrounds the issue of sensor recruitment for coordination. In the specific context of RHex, this issue emerges most sharply as we take the first steps toward improving and effectively utilizing the robot's sensory suite. The current implementation does not afford any task level perception whatsoever. However, future versions will employ a broad array of sensors proposed to increase RHex's energy efficiency and afford autonomous locomotion without a human operator. We describe recent work toward the analytical machinery that can inform our efforts to improve and refine this device regarding general questions of coordination as well as specific issues of how to introduce simple task level sensors for the purpose of instrumenting low bandwidth feedback. An emerging understanding of two extreme approaches - "clock" vs. "reflex" - begins to inform our efforts to select the appropriate coordination architecture from a wide spectrum of possibilities that they seem to delimit.

Acknowledgements: The Computational Neuromechanics Project is supported by DARPA/ONR under grant N00014-98-1-0747. We thank Martin Buehler, Uluc Saranli, Phil Holmes, and the other members of the project for their shared insights and help with the specifc questions addressed in this paper.

Roy Kornbluh, Ron Pelrine, S. Venkat Shastri, Qibing Pei
Electroactive Polymer Artificial Muscle
SRIInternational

Just as the dynamic capabilities of biological creatures are critically determined by the actuation characteristics of natural muscle, the dynamic capabilities of robots are critically determined by the characteristics of their actuators. To achieve biomimetic motion, actuators must be able to reproduce the important features of natural muscle such as power and energy density, stress and strain, speed of response, efficiency, controllability, and mechanical impedance. Pneumatics and hydraulics are often employed to make up for the limitations of electromagnetic actuators; however, these approaches introduce additional complexity and difficulty in control.

Among electrically activated „smart materials,‰ electroactive polymers (EAPs) have been the focus of much recent attention as the potential basis for such „artificial muscle‰ actuators. For the past 8 years, SRI has been developing an electroactive polymer technology based on the electric-field-induced deformation of elastomeric polymer dielectrics with compliant electrodes. These dielectric elastomer materials have produced strains in excess of 100% and energy densities exceeding those of other fast-acting electrically activated materials. A wide variety of actuator configurations have been demonstrated for a wide range of applications such as robots, microdevices, loudspeakers, pumps, adaptive optics, rotary motors, and oscillators. Linear artificial muscle actuators for robots have been demonstrated on walking, flapping-wing and serpentine robotic devices. Recent testing by experimental biologists has confirmed that these dielectric elastomer artificial muscles can indeed reproduce many of the important characteristics of natural muscle. Continuing work is focusing on applying these actuators to robots and on identifying the best ways to exploit biomimetic features such as preflexive control, elastic energy storage, and embedded proprioceptive feedback. Improvements to the materials, fabrication processes, electronic driving circuits, and systems integration are also being addressed.

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Moving eyes: visual sensors with gaze control
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Nearly all animals with good vision can move their eyes. In most cases, mobility of the direction of gaze turns out to be an essential feature inherent to the visual data acquisition process. This fact is usually overlooked in engineered implementations of visual sensors, which contributes to explain the modest performance of electronic visual sensors compared to their biological counterparts. In the frame of several projects, we have developed systems and devices providing visual sensors with the capability of shifting their field of view quickly, accurately and in a useful pattern.

An optical device made of two microprism gratings actuated by electrical motors has been built, which can deflect light by up to 45 degrees in any direction with respect to the axis of the focusing optics. Starting at rest, the direction of gaze can jump toward any other point and stabilize within 45-100 ms.

A custom analog VLSI control chip implements saccadic exploration behavior. Under guidance of a low-resolution electronic retina watching the wide field of view accessible by eye movements, this chip determines the sequence and timing of fast jumps (saccades) of the dual-microprism light deflection device mounted onto a high-resolution retina (comparable to the fovea found in humans and many other animals). Fovea movements provide high-resolution access to a wide field of view without requiring a tremendous number of pixels. They also eliminate the need of position-invariant pattern recognition algorithms because individual patterns composing a complex scene can be centered onto the fovea successively in time.

Another custom analog VLSI control chip implements simple smooth pursuit behavior. When a single object moves in the visual field, the chip controls the microprism gratings of the light deflection device on the basis of the position of the object on the high-resolution retina ("fovea") in such a way to keep it centered. Operation has been demonstrated at velocities up to 50 degrees per second in visual angle. Smooth pursuit relaxes pixel bandwidth requirements in the presence of moving objects.

Instead of keeping the image of an object fixed during visual data acquisition, it can be beneficial to keep it sliding with respect to the visual sensor if the latter is designed to take advantage of this situation. Continuous image movements cause an array of photoreceptors to scan the image continuously instead of sampling it on a discrete grid, thereby providing a potential improvement in effective resolution. Scanning also turns spatial features into temporal fluctuations of the light intensity received by individual photoreceptors. The AC component of the light intensity reveals the spatial texture of the image on the scanning path. Offsets due to device mismatch affect only the DC component and can be filtered out, thereby eliminating a major cause of fixed-pattern noise affecting ordinary visual sensors. A microsystem implementing this approach is under development as of this writing.

This work has been carried out partly at CSEM SA in Neuchatel, Switzerland, and partly at Caltech in Pasadena, USA. Thanks are due to Steve Gyger, Friedrich Heitger, Patrick Debergh, and Ania Mitros for their technical contributions to the various projects summarized herein.

Nicol McGruer, George Adams, Paul Zavracky, Thieu Truong
Terrence Barnes, Xiaoqing Lu, and Juan Carlos Aceros
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Biomimetic Flow and Contact/Bending MEMS Sensors

Contact/bending and flow sensors have been designed, analyzed, fabricated, and tested. These sensors are to be mounted on flexible antennae and on other parts of the robot's body in order to provide a sense of touch for ambulatory robotic lobsters and scorpions. These biomimetic vehicles are designed to mimic some of the behavior patterns of real lobsters and scorpions [1].

Two contact/bending sensors have been developed - a “standard” sensor and a “stopper” sensor. The *standard sensor* and the *stopper sensor* are cantilever beam type microswitches fabricated on thin flexible substrates. These sensors were fabricated using the Northeastern University Metal Micromachining (NUMEM) process [2]. The purpose of the stopper sensor design is to increase the dynamic range and alleviate the sensitivity limitations that are inherent in the standard sensor design. Tests have shown the standard sensors close at a substrate radius of curvature that is 25% greater than the design values. When used in a linearly tapered antenna, the bending response of the antenna, coupled with the sensors, allows fluid flow and object contact to be distinguished.

A *hair like* MEMS flow sensor has been designed, analyzed, fabricated, and tested. The current generation of sensor consists of a surface micromachined switch with a complex cantilever shape. A portion of the sensor is bent at a right angle to the substrate and to the flow direction. The fluid flow produces a pressure on the sensor; sufficient pressure causes the switch to close at the designed flow rate. The analysis of these devices consists of using incompressible fluid mechanics to determine the pressure acting on the sensor and beam theory to model the resulting deflection of the sensor. The first set of flow sensors was designed to close at flow velocities of 0.5, 1.0, 3.4, and 5.4 m/s. The area of the hair or paddle, which lies in the flow, is varied in order to obtain sensors that close at different flow rates. The results of testing agree well with the analytical predictions. Although these flow sensors are unidirectional, an array of four sensors at each point can be used to determine the flow velocity and direction. With appropriate packaging, we envision a rugged class of sensors with applications in robotics and biomedical fluid flow measurement.

References:

[1] Ayers, J., 1995, "A Reactive Ambulatory Robot Architecture for Operation in Current and Surge" *Proceedings of the Autonomous Vehicles in Mine Countermeasures Symposium*, pp. 15-31.

[2] Zavracky, P.M., McGruer, N.E., and Majumder, S., 1997, "Micromachined Switches Fabricated Using Nickel Surface Micromachining" *IEEE/ASME Journal of Microelectromechanical Systems*, Vol. 6, pp. 3-9.

Robert Michelson
Georgia Tech
Entomopter

The Entomopter is a multimode autonomous robot that is capable of flight, ambulatory locomotion, and swimming behaviors in a single vehicle. Autonomous navigation is based on a combination of attraction and avoidance behaviors deriving input from both an integrated optic sensor for detection of chemical species (or alternately a sensor for a specific type of radiation), and an ultrasonic swept beam ranging device.

For indoor flight operations, the flapping wing is considered the best approach. Other modes of locomotion (crawling or swimming) are based on the same actuation system as that used for flapping wing flight, but do not involve the complexity, precision, or energy expenditure associated with flight. For this reason, current development has concentrated on the problems associated with flight using flapping wings.

Biomimetics was the starting point for the Entomopter design, but rather than attempting to replicate biological kinematics and aerodynamics, improved systems have been devised to leverage what is observed in biological systems to produce a machine that is manufacturable, controllable, and able to generate the power necessary to fly from onboard energy sources. Just as wheels are superior locomotors under certain circumstances, but are not a common form of locomotion for biological systems, so the Entomopter has extended its design beyond the biological baseline in some areas.

The Hawk Moth (Manduca sexta) was chosen as a base line model for the wing aerodynamics. The flapping mechanism for the Entomopter has been extended beyond that of the Hawk Moth to provide a resonant single-piece construction that takes advantage of torsional resonance in the Entomopter fuselage to recover flapping energy as is a common to flying insects which temporarily store potential energy in either the muscles or exoskeletal parts (resilin).

The same structure that provides wing flapping also scans a frequency modulated continuous wave ultrasonic beam to provide front, side, and down-looking range measurements for obstacle avoidance and altimetry in a fashion similar to that employed by bats.

Stability and control in flight as well as navigation is achieved by actively modifying the lift of each wing on a beat-to-beat basis using pneumatic control of the air circulating over the beating wing. Positive lift can be generated on not only the down beat but the up beat as well. Coefficients of lift exceeding the theoretical maximum by 500% for the given wing shape can be achieved, without the complexity of physical angle-of-attack mechanisms.

A chemically fueled reciprocating chemical muscle has been designed and is in its third generation of development. This actuator system has demonstrated 70 Hz reciprocation rates with throws and evolved power levels necessary to support flight, crawling, or swimming of a self-contained Entomopter system.

Gavin Miller
SnakeRobots.com
Mechanisms for undulatory locomotion

This paper describes a series of mechanisms designed to explore the use of undulatory motion for locomotion on land. These were inspired by the success of biological snakes. Starting with planar mechanisms the paper explores simple implementations using off-the-shelf radio-controlled servos with direct coupling. Later models introduce a novel biologically-inspired mechanical design. This employs a single universal joint at the top of the robot cross-section combined with two servos in opposition linked by ball-jointed rods. The paper describes the advantages of this mechanism and the several gaits that it enables. The paper concludes with a discussion of snake-robot mechanisms that might locomote without wheels and describes the design goals for the next prototype.

Ralf Möller
Artificial Intelligence Lab, University of Zurich
Visual Homing

Insects like bees and ants use visual landmark navigation to return to previously visited locations. Experiments revealed that the insects store a rather unprocessed image of the surroundings of the target location and derive a home vector from a comparison between this "snapshot" and the current view [1,2]. The algorithm for the matching of the two views and the computation of the home vector is described in the "snapshot model" [1]: each feature in one view is paired with the closest feature of the same type in the other view, and from each pair two vector contributions to the home vector are derived, resulting in movements that reduce the differences in bearing and size between the features, respectively. Experiments with the mobile robot Sahabot-2 demonstrated that navigation with the snapshot model is possible with high precision under real-world conditions [3].

A behavior similar to the snapshot model is obtained in the "average landmark vector model" [3], which is more parsimonious than the snapshot model, since instead of a snapshot image only a "average landmark vector" with two elements has to be stored, and the matching process is simplified to a single vector subtraction. The average landmark vector is obtained by averaging unit vectors that point towards the landmark features. The parsimony of this model allowed to implement the landmark navigation method in purely analog hardware mainly based on discrete operational amplifiers [4,5]. Visual input from a circular array of 32 photodiodes is processed by edge filters with lateral inhibition. An egocentric average landmark vector (two voltages) is obtained by weighting and integrating the edge-filtered signals. Using an electronic magnetic compass, the average landmark vector of the target position is transformed into geocentric coordinates and stored as analog values using capacitors. In another location and orientation, the stored snapshot vector is transformed back to egocentric coordinates and subtracted from the egocentric average landmark vector derived from the current visual input. The result is a vector pointing approximately to the target location. Tests of the hardware have been performed in an arena with black landmarks presented on a white background. The results support the hypothesis that the mechanisms underlying landmark navigation might be relatively simple, especially since analog ("neuromorphic") implementations are partly facing the same problems as biological nervous systems. From the engineering perspective, analog implementations are attractive because of inherent parallel processing, fault tolerance, low power consumption, and the elimination of domain transformations between analog and digital processing.

We are currently investigating how the parsimonious homing methods used by insects can be applied for navigation in office environments [6].

[1] B. Cartwright, T. Collett. Landmark learning in bees. Journal of Comparative Physiology A, 151:521-543, 1983.
[2] R. Wehner, F. Räber. Visual spatial memory in desert ants, Cataglyphis bicolor (Hymenoptera: Formicidae). Experientia, 35:1569-1571, 1979.
[3] D. Lambrinos, R. Möller, T. Labhart, R. Pfeifer, R. Wehner. A mobile robot employing insect strategies for navigation. Robotics and Autonomous Systems, special issue: Biomimetic Robotics, 30:39-64, 2000.
[4] R. Möller. Visual Homing in Analog Hardware International Journal of Neural Systems, special issue: Neuromorphic Engineering, 9(5):383-389, 1999
[5] R. Möller. Insect Visual Homing Strategies in a Robot with Analog Processing. Biological Cybernetics, special issue: Navigation in Biological and Artificial Systems (to appear)
[6] R. Möller, D. Lambrinos, T. Roggendorf, R. Pfeifer, R. Wehner. Insect Strategies of Visual Homing in Mobile Robots. In: T. Consi, B. Webb: Biorobotics, AAAI Press (to appear)

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Experimental Study of Two-Joint Dolphin Robot

We produced a self-propelled two-joint dolphin robot which is a simplified model of fast swimming animals, and estimate the experimental values of the consumed power and the propulsive efficiency by measuring the torque and angular speed of the joint.

The total body length of the robot is 1887 mm, which is similar to the length of actual fast swimming animals. The robot is composed of a streamlined body and a rectangular caudal fin. The first joint is actuated by an electric starter motor for a car, which has the maximum output power of 7.4kW. And the rotational motion of the motor is transformed into the swing motion of the anterior part of the body by using gears and cranks. The second joint is moved passively by springs. In addition, the yaw direction of the robot can be varied with a yaw joint, which is controlled with a radio controller on the ground, in order to make the robot swim along the straight rope for the measurement of the propulsive speed.

First, we measure the drag by towing the robot and calculate its drag coefficient. Next, we measure the propulsive speed and the torque and angular speed of the joint simultaneously for various input power of the air motor and various frexibility of the second joint. From the torque and angular speed, we can calculate the consumed power, and, (with the propulsive speed the drag coefficient), the propulsive efficiency. The robot attained a propulsive speed of 1.9 m/s and a propulsive efficiency of 0.65.

Roger D. Quinn, Gabriel M. Nelson, Roy E. Ritzmann
Case Western Reserve University
Toward the development of a useful hexapod robot

In order for a robot to perform missions in a natural or urban environment it must be strong, powerful and agile. To capture agility, we turn to insects as useful models. We are designing robots that capture the important movements and dynamics of the cockroach as it runs on horizontal surfaces and climbs over barriers. However, keeping in mind the ultimate mission requirements, we have used strong aluminum construction and pneumatic actuators with beneficial power-to-weight characteristics. These design constraints have created many challenges that must be overcome to accomplish this goal. However, we believe that the benefits of truly agile and capable machines provide ample reasons for meeting these challenges.

First, the locomotion behavior of cockroach during walking, running and climbing must be well understood and the salient features must be extracted from extraneous properties in order to implement them in a useful vehicle. We have reported previously on how we incorporated walking kinematics into a dynamic simulation in order to extract necessary degrees of freedom for each pair of legs. We now report new findings on climbing over various height blocks. Again we have coupled kinematic studies with electrophysiology and dynamic simulation to understand the roles of each leg in this important task. Next, to provide efficient control of the required leg joints, we developed a hierarchical system that segregates control function in a manner similar to the gross properties of the animal's central nervous system. A global circuit oversees body motion and posture as do the higher centers of the animal. An intra-leg network coordinates the joints of each leg and encourages desired foot motion, much like the local control circuits found in each insect ganglion. This neural network performs inverse kinematics and uses proprioceptive information to coordinate the various joints so as to smoothly move the foot to desired locations. Positive load feedback, from load sensors in the skeleton, is shown to be important for production of force in both the animal and the robot. An inter-leg network as described by Cruse coordinates the various legs and adjusts the robot's gait, as do interganglionic connections in the insect.

Finally, the choice of actuators is critical. Cockroach dynamics and energy efficiency require actuators with properties similar to muscle. We show that McKibben artificial muscle has these desirable properties including an inherent elasticity that is tunable independent of motion. The dynamics of the exoskeleton design are also important for ultimately capturing efficient movement. To this end, we present the design of Robot IV, which has the dynamics of *Blaberus* cockroach, an exoskeleton design and is actuated by the more muscle-like McKibben artificial muscles.

Mandyam V. Srinivasan
Centre for Visual Sciences, Australian National University
Vision and Navigation in Flying Insects

Although most insects lack stereo vision, they use a number of ingenious strategies for perceiving their world in three dimensions and navigating successfully in it. For example, distances to objects are gauged in terms of the apparent speeds of motion of the objects' images, rather than by using complex stereo mechanisms. Grasshoppers estimate the distance to targets by moving their heads from side to side, and measuring range in terms of the speed of the target's image on the retina. Bees distinguish objects from backgrounds by sensing the apparent relative motion at the boundary between object and background. Bees flying through a tunnel maintain equidistance to the side walls by balancing the apparent speeds of the images of the walls. The speed of flight in the tunnel is regulated by holding constant the average image velocity as seen by the two eyes. Bees landing on a horizontal surface hold constant the image velocity of the surface as they approach it, thus automatically ensuring that flight speed is close to zero at touchdown. Foraging bees gauge distance flown by integrating optic flow: they possess a visually-driven "odometer" that is robust to variations in wind, body weight and energy expenditure. I shall describe some of this work and outline applications of some of these strategies to the design of autonomous, visually-guided robots.

Barbara Webb
Stirling University, Scotland
Phonotaxis in crickets and robots

Phonotaxis is active sound localisation. Female crickets can find male crickets by walking towards the calling song they produce. Using a robot to model this behaviour we can show that a relatively simple control mechanism suffices to reproduce many different aspects of the behaviour including recognition and choice between sounds. The mechanism exploits the inherent carrier frequency filtering of the pressure difference receiver ears, and the inherent temporal pattern filtering of realistic neural time constants. In recent work we have combined the phonotaxis behaviour with an optomotor response.

Gernot Wendler
Institute of Zoölogy, Universitat Köln

From neural activity patterns to aerodynamic forces:
The flight system of the tobacco hawkmoth Manduca sexta.

The known principles of motor control and signal processing in insect walking and insect flight systems will be compared. This comparison leads to the conclusion that it may be much easier to analyze, and hence to simulate, the central nervous control of flight systems than of walking systems.

The current research focuses on the flight system of the tobacco hawkmoth Manduca sexta. Manduca is a neurogenic flier with superb flight capabilities. The talk deals with the chain from electrophysiological recordings of flight muscle activity to wing movements and to aerodynamic resultants during tethered flight. The correlation of the data collected with these methods gave valuable information on the underlying functional principles. However one cannot completely understand the causality of the system from these correlations. For example the change of activity of a certain muscle during a given flight manoeeuvre does not necessarily reveal the function and importance of this muscle in this specific situation. We therefore present a new method: the de-efferented preparation. After removing the nervous system, it is possible to control the timing of muscles´ contraction by stimulating them via chronically implanted wires. These results gave new insights into the role of elasticity and resonance of the insect´s thorax and can reveal the function of steering muscles in the activity concert of the set of flight muscles. One can also learn how to control flight manoeuvres in flying microrobots that are based on a similar architecture.

Cricket Wilbur, William Vorus, Yusong Cao, Scott Currie
Northeastern University, University of New Orleans, UC Riverside
A Lamprey-Based Undulatory Vehicle

We are building a biomimetic robot based on a simple vertebrate model, the sea lamprey. Lamprey swim by rhythmic lateral undulations of the body axis. Kinematic analysis of body curvature demonstrates that swimming behavior is organized into lateral flexion waves that propagate either rostro-caudally or caudo-rostrally and generate a peak of thrust as each flexion wave passes the cloaca. 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. The period and amplitude of their underlying curvature thus characterize flexion waves. A behavioral library of the lamprey has been developed by reverse-engineering sequences of lamprey behavior. This library includes various forms of swimming, crawling, burrowing and withdrawal.

We adapted a conservative command neuron, coordinating neuron, central pattern generator architecture to realize a finite state machine to generate lateral axial undulations in a 5 segment undulator that uses a polyurethane “notochord” and segmental muscles fabricated from shape memory alloy. The actuators are activated by a CPG-based pulse-width modulation system that allows graded recruitment of force. Control and power electronics are housed in a watertight hull. The system maintains trim and static roll stability using close-cell foam buoyancy elements and a lead shot “keel” covered by a Lycra™ skin. We are incorporating a sensor suite including a compass, pitch and roll inclinometers, accelerometers and both look forward and look down sonar range finders.

A beam model was developed for the undulator that assumed that the neutral axis of a section of the composite beam structure (the notochord plus the nitinol wires on each side of the notochord) is on the side of the notochord where the nitinol wire is electrically deactivated. The neutral axis switches back and forth from one side to the other side as the beam undulates. Given a displacement of the notochord (e.g. the wakeless motion) and external load, this model can provide the strain and stress of the wire, as well as the stress in the notochord, as functions of time for each section. The beam model was coupled with the 3-D slender body hydrodynamic model for external hydrodynamic load. This coupled model can be used for the prediction or evaluation of the external hydrodynamic loads, the internal load (stress), the input power, the propulsion efficiency, and the motion of the undulator.

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Mark A. Willis
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Odor-guided Navigation in Fluid Media

Many animals, ranging from bacteria to insects, fish and mammals, use air- or water-borne plumes of odor molecules to locate distant unseen resources. Remarkably, the movement tracks that many animals produce when tracking odor plumes have a very similar side-to-side zigzag shape whether walking, swimming, or flying (however, similar-looking behavior does not necessarily indicate similar underlying mechanisms). Such similarity across disparate species and conditions suggests that there may be something fundamentally ‘good’ about this approach to tracking chemical plumes. Moth orientation to odor plumes is an ideal system in which to study the fundamental algorithms that underlie orientation to chemical plumes because there so much information available about every step of the pathway - from odor detection at the receptor level to the motor outputs that constitute behavior. This also makes it an excellent model for the development of robotic systems capable of tracking an odor plume to it’s source.

Recent collaborative work centered in our lab has taken a simulation modeling approach to testing biological hypotheses explaining odor-tracking behavior in flying moths. We have taken a two-pronged approach: one constructs simulation models based explicitly on published hypothetical mechanisms from moths; the second is only partially constrained by data from odor-tracking moths. For the most part our simulations are organized around what is known about the sensory systems, behavior and control systems of real moths to more fully understand the complex interaction between the odor stimulus, sensory processing, interacting control systems, and ongoing centrally organized behavior. Our simulation experiments have tested behavioral hypotheses generated from experiments with real moths, both in laboratory wind tunnels and in the field, and in some cases posed new hypotheses. The rate of successful source location of our initial simulations only rarely approached that of real moths, and then only when the simulations were operating outside of the parameter space available to real moths. However, the simulations failed in characteristic and revealing ways. Typical results revealed that particular search strategies were extremely sensitive to the performance capabilities of the agent executing that strategy: specifically, latencies involved in sensory processing and motor control. Results such as these inform an guide subsequent behavioral experiments. We are currently in the process of modifying these algorithms to further test biological hypotheses by using them as control systems in odor-tracking robots.

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Shape Memory Alloy Actuators Applied to Underwater Robots

We are developing two types of underwater vehicles based on the lobster and sea lamprey. We developed a biomimetic artificial muscle system based on the shape memory alloy, Nitinol. When annealed at high temperature, Nitinol assumes a compact (austenite) crystalline structure. When cooled a SMA wire can be mechanically stretched to a looser (martensite) crystalline structure with strains of up to 6%. When reheated above an austenite transition temperature a stretched wire can contract at a rate that depends on applied current and stress and a 250µ wire can produce stresses of up to 1kg. By operating antagonistic pairs of nitinol actuators underwater to facilitate cooling to the martensite transition temperature we can form mechanical oscillators with bandwidths up to 3-4 hz depending on wire diameter, thermal dielectric and ambient temperature. Fabrication details are critical in the operation of these artificial muscle systems underwater.

During heating, the proportion of martensite state nitinol that converts to austenite and thus the amplitude of contractions depend on the amplitude of applied current. We grade the force of nitinol muscles through pulse width modulation with constant current regulation. We have adopted the size principle of neuromuscular recruitment by discretizing pulse widths into small, medium and large pules widths that correspond to the small, medium and large motor neurons found in lobster neuromuscular synergies. Our biomimetic controller thus selects different recruitment levels based on the requirements of the behavior and both the stress and strain of contractions can be controlled in a graded fashion. Nitinol is a smart material and individual modules must be trained with regard to the desired stroke. Training is achieved by repetitively contracting the module against a load. Increases in the training load increase the trained stroke. Once trained, the modules can maintain their stroke for up to 30,000 cycles.

We have modeled the static dynamics of the control of posture in the ambulator system. The posture is controlled by two joints that produce elevation / depression and extension / flexion around two joints that operate in the plane orthogonal to the body axis. Gradients in the magnitude of depression from rostral to caudal control the pitch while gradients between the two sides control roll. Symmetric graded activation of the depressors controls the height of the vehicle. Our model allows us to predict the magnitude of pitch, roll and height biases from PWM of the individual muscle modules.

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