GEORGIA INSTITUTE OF TECHNOLOGY'S GLOBAL LEARNING AND CONFERENCE CENTER

May 10–12, 2006

CB!D

center for biologically inspired design

2006 INTERNATIONAL SYMPOSIUM FOR BIOLOGICALLY INSPIRED DESIGN IN SCIENCE AND ENGINEERING

PROGRAM GUIDE & ABSTRACTS

themes

- Biologically inspired materials
- Biologically inspired movement/movement control strategies
- Biologically inspired sensing mechanisms and strategies
- Interdisciplinary education in biologically inspired design and at the interface between biology and engineering

Biologically-inspired design focuses on the use of biological processes, organisms and systems as potential sources of innovative solutions to vexing technological or engineering problems.

Our goal is to facilitate interdisciplinary collaboration between biological scientists and engineers to encourage innovation to increase the efficiency, practicality and sustainability of human solutions

This conference is supported by funds from the Office of the Vice Provost for Research, the Institute of Sustainable Technology and Development, the School of Industrial and Systems and Engineering, and the program for Engineering Design at NSF.

THE CENTER FOR BIOLOGICALLY INSPIRED DESIGN AT GEORGIA TECH

Program Guide and Abstracts

GENERAL INFORMATION:

All sessions will be held in Auditorium 236 in the Global Learning and Conference Center at Technology Square (84 5th Street NW).

***Registration* and *additional information* on the location of dining and other events will be available at the registration table outside of room 236. These events also will take place at the Global Conference Center.**

Symposium Schedule

Wednesday May 10th

5:30-7:00	Registration-Welcoming Social
7:00-9:00	Opening Banquet: Atrium

Thursday May 11th Auditorium 236

8:00	Registration
8:30-10:00	*Bio-Materials I*
10:00-10:30	Coffee Break/Registration
10:30-12:30	*Bio-Materials II*
12:30-1:45	Lunch Break
1:45-3:15	*Biologically-Inspired Sensing and Sensing Strategies I*
3:15-3:30	Break
3:30-5:15	*Biologically-Inspired Sensing and Sensing Strategies II*
5:15-6:45	Poster Session and Social: Atrium
6:45	Dinner: Atrium

Friday May 12th Auditorium 236

8:00- 9:00	Registration
9:00-10:30	*Interdisciplinary Education I*
10:30-10:45	Coffee Break
10:45-12:15	*Interdisciplinary Education II*
12:15-1:30	Lunch Break
1:30-2:30	*Biologically-Inspired Locomotory Strategies I*
2:30-2:45	Break
2:45 - 4:30	*Biologically-Inspired Locomotory Strategies II*

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Detailed Session Schedule

Thursday May 11th

8:30-8:45 Opening Remarks:

Jeannette Yen, Director, Center for Biologically Inspired Design, Georgia Tech
Gary Shuster, Dean, College of Sciences, Georgia Tech

Bio-Materials I:

Chair Ken Sandhage School of Materials Science & Engineering

8:45-9:30 Stanislav Gorb. *Locomotory Attachment Devices in Animals: Mechanisms and Biomimetic Implications*

9:30-9:45 Adam P Summers, *Interesting properties of cartilaginous skeletons*
9:45-10:00 Todd A Blackledge, *Spider silk: a 400 million year experiment in materials science*

BREAK--

Bio-Materials II:

Chair Nils Kroger School of Chemistry

10:30-11:15 Mark Hildebrand and Aubrey K. Davis. *Structural Control, Molecular Components, and Multi-level Regulation of Biosilicification Diatoms*

11:15-11:30 Heather Luckarift, Lorena Betancor, Cecile Berne and Jim Spain. *Enzyme immobilization by silification reactions*
11:30-11:45 Andreas Solga, Zdenek Cerman, Wilhelm Barthlott. *Lotus-Effect®: Biomimetic super-hydrophobic surfaces and their application*
11:45-12:30 Yoseph Bar-Cohen. *Biologically inspired technologies using artificial muscles*

LUNCH--

Biologically-Inspired Sensing and Sensing Strategies I:

Chair Bruce Walker School of Psychology

1:45-2:30 Rolf Müller *Biosonar-Inspired Design - Past, Presence, Future*

2:30-2:45 Jennifer Talley, Hillel J. Chiel Edward B. White and Mark A. Willis. *Using simulations to understand simple rules for odor tracking*.
2:45-3:00 Adam Rutkowski, Mark Willis and Roger Quinn. *Development of an Aerial Three-Dimensional Odor Tracking Strategy*
3:00-3:15 Hang Lu. *What we can learn from a worm's brain*

BREAK---

Biologically-Inspired Sensing and Sensing Strategies II:
Chair Paul Corballis School of Psychology

3:30-4:15 Mitra J. Hartmann. *Novel Tactile Sensing Systems Inspired by the Rat Vibrissal Array*

4:15-4:30 Chang Liu, Joseph Humphrey, Sheryl Coombs, Douglas Jones, and Vladimir Tsukruk. *Artificial Haircell and Artificial Lateral Line Sensors: Design, Material, and Application*

4:30- 4:45 M.J McHenry, S.M. van Netten. *Flexible flow filters in fish: the mechanics of hydrodynamic reception*

4:45-5:00 Arthur G. Shapiro. *Counter-shading, camouflage, and the design of visual illusions*

5:00-5:15 C. W Kotas, Minami Yoda, M. and Peter Rogers. *Acoustically Induced Flows in the Fish Ear*

5:15-6:45 Poster Session and Social

6:45 *DINNER* ---

Friday May 12th

Interdisciplinary Education I:
Chair Mohan Srinivasarao School of Polymer, Textile and Fiber Engineering

9:00-9:45 Robert Clark. Biologically *Inspired Materials and Material Systems*

9:45-10:15 Marc Swackhamer, *Biomimicry: Nature as Model, Mentor, and Measure*

10:15-10:30 Scott Turner. *Emergent homeostasis and termite mounds. A template for living structures*

BREAK---

Interdisciplinary Education II:
Chair Craig Tovey School of Industrial and Systems Engineering

10:45-11:30 Satyandra Gupta. *Using Biologically Inspired Robots as Case Studies for Teaching Bio-Inspired Product Development*

11:30-12:00 Shu, Lily (Li) *Generalizing Biologically Inspired Design for Problem Solving*
12:00-12:15 Bert Bras *Inclusion of biologically inspired design into mechanical engineering design classes*

LUNCH--

Biomechanics and Biologically-Inspired Locomotory Strategies I:
Chair Lena Ting School of Biomedical Engineering

1:30-2:15 Robert J. Full. *Galloping Ghosts, Gripping Geckos and Bipedal Bugs: Bio-Inspired Robots, Adhesives and Artificial Muscles*

2:15-2:30 Frank Grasso. *Modeling Octopus Suckers*

BREAK--

Biomechanics and Biologically-Inspired Locomotory Strategies II:
Chair Young Hui Chang School of Applied Physiology

2:45-3:30 George Lauder. *Biodesign for Aquatic Propulsion: Fish Fins as Flexible Thrusters*

3:30-3:45 AnnMarie Polsenberg Thomas, John Dabiri, and Joel Burdick. Synthetic Jets: *Learning from Jellyfish*
3:45-4:00 Kartik Sundar, Lena H. Ting and Stephen P. DeWeerth. *Nonlinear Intrinsic Muscle Stiffness and Damping as an Effective Autonomous Controller*
4:00- **Closing Remarks: Marc Weissburg** School of Biology

Event sponsored by the **Center for Biologically Inspired Design at Ga Tech**, with funds from the Office of the Provost for Research, the Institute for Sustainable Technology Development, the School of Industrial and Systems Engineering, and the Program for Engineering Design at the National Science Foundation. Thanks also to Alex Collins, Len Yen, Joy Worthen and Tom Becher.

Program Guide and Abstracts

Poster Session-May 11th 5:15-6:45

Chang, Y.-H.. *Toward a behavioral template for intralimb compensatory mechanisms during legged locomotion.*

Daltorio, Kathryn, Terence E. Wei, Stanislav N. Gorb, Jason M. Funt, Roy E. Ritzmann, and Roger D. Quinn . *Enhancing Robotic Mobility Through Insect Strategies*

Kamal, Firdous, Diane Ramos , Alexander N. Cartwright, and Antonia Monteiro. *Laser-induced gene expression in live transgenic butterflies in a controlled spatial and temporal fashion*

Kotas, C.W, Minami Yoda, M. and Peter Rogers. *Visualizations of Steady Streaming Flows: Could Fish Ears Be "Auditory Retina"?*

Koehler, Stephan. *How to swim in sand*.

Migliore, Shane, Edgar A. Brown, and Stephen P. DeWeerth. *Biomimetic Actuators for the Control of Robot Joint Compliance.*

Nakrani S, C Tovey. *Resilient Honey Bee Biomimetic Web Server Allocation*

Pulido, Gonzalo. *Biomimetics: Breathing Skin*. Florida International University

Reap, John. *Small scale surface roughness and a principled approach to sustainable engineering*

Rutter, Brandon, Laiyong Mu, Roger D. Quinn, and Roy E. Ritzmann.. *A Model that Transforms Insect Electromyograms into Pneumatic Muscle Control*

Scrivens, Jevin, Lena Ting, and Stephen DeWeerth. *Scaling of Feedback Control Gain with Stance Width*

Shian, Samuel, Ye Cai, Shawn Allan, Michael Weatherspoon, and Kenneth H. Sandhage *Syntheses of Nanostructured Ceramic Microparticles with Selectable Intricate 3-D Shapes and Tailored Chemistries via **B**ioclastic **a**nd **S**hape-preserving **I**norganic **C**onversion* **(BaSIC)**

Weissburg, Marc, David Dusenbery, Don Webster. *Strategies for navigating through turbulent odor plumes—a crab-inspired approach*

Zimmerman, Amanda, Jeremy Lewi, Isaac Clements, Terrence M. Wright, Stephen P. DeWeerth, Robert J. Butera. *Hybrid Neural Microsystems: Bridging Neuroscience and Engineering through the development of Co-Advisory Relationships.*

Program Guide and Abstracts

ABSTRACTS

Bar-Cohen, Yoseph. *Biologically inspired technologies using artificial muscles*
Jet Propulsion Lab (JPL)/Caltech

Abstract: Nature is the largest laboratory that ever existed and ever will. In addressing its challenges through evolution Nature tested every field of science and engineering leading to inventions that work well and last. Nature has “experimented” with various solutions and over billions of years it has improved the successful ones. It has always served as a model for mimicking and inspiration to humans in their efforts to improve their life. Adapting mechanisms and capabilities from nature and using scientific approaches led to effective materials, structures, tools, mechanisms, processes, algorithms, methods, systems and many other benefits. The subject of copying, imitating, and learning from biology was coined Biomimetics by Otto H. Schmitt in 1969. This field is increasingly involved with emerging subjects of science and engineering and it represents the studies and imitation of nature's methods, designs and processes. Biologically inspired technologies are making it possible to consider developing such devices as prosthetics that feel and operate like the "real thing" as well as engineering robots that look and behave as human and animals. Mimicking Nature involves many challenges and requires significant technology advances. To promote advances in the field of electroactive polymers (EAP) that is know as artificial muscles, the author posed in 1999 an armwrestling challenge for a match between human and a robotic arm that is driven by these materials. A contest is now held annually and it is providing a measure of the advances in the field of EAP and the ability to mimic the performance of muscles. A review will be given of selected areas that were inspired by nature with emphasis on EAP and an outlook for potential future development in biomimetics.

Program Guide and Abstracts

Blackledge, Todd A. *Spider silk: a 400 million year experiment in materials science*
Department of Biology, University of Akron, Akron, OH 44325-3908, USA

Abstract: Spider dragline silk has a number of enticing properties for the production of biomimetic fibers, in particular high tensile strength and extreme toughness. However, silk also plays an integral role in the ecology of spiders including protection against predators or the environment, capture of prey, dispersal, communication, and reproduction. Furthermore, orb-weaving spiders can produce at least seven different types of silk that are composed of different sets of proteins. The material properties of these silk fibers result from how the constituent proteins of silk fibers are assembled and interact with one another and are likely to have been shaped by natural selection on the ways in which each silk interacts with the environment. Therefore, the biomechanical study of spider silk can potentially link together research ranging from the evolution of silk genes through the ecological function of webs or other silk structures. Here, I discuss how research on the biological diversity of silks spun by spiders can facilitate efforts to synthesize biomimetic fibers.

Program Guide and Abstracts

Bras, Bert. *Inclusion of biologically inspired design into mechanical engineering design classes*
School of Mechanical Engineering, Georgia Institute of Technology

Abstract. In this talk, we will present our experiences with including biomimetic principles into mechanical engineering design classes. The goals are 1) to expose engineering students and practitioners to biomimicry and 2) to gain insight into the efficiency and effectiveness of using biomimetic approaches to solving engineering design problems. Specifically, our experience with ME 4182 – Capstone Design will be highlighted. The initial experiment consisted of including biology undergraduate students as project consultants for the engineering design teams. Experiences from the engineering students (through surveys and informal feedback), biology students and faculty will be presented. Selected projects will be highlighted to illustrate the effectiveness, shortcomings, and barriers to biomimetic approaches. Lessons learned and suggestions for future experiments, implementations and expansion will be given.

Program Guide and Abstracts

Clark, Robert. *Biologically Inspired Materials and Material Systems*
Duke University.

Abstract. It is clear that our biological and medical community is now at a point of incredible opportunity. The collective biological sciences (biological, biophysical, biochemical, biocomputational, and biomedical) have generated a plethora of information regarding complex biological systems, especially at the microcellular and nanomolecular levels. It is time to bring these research advances into the core curriculum for all students interested in careers that require a more detailed and mechanistic understanding of the biological world, disease, and medicine.

We recognized several years ago that a more rigorous mapping of engineering onto the biological sciences might yield more mechanistic information about nature's own technologies. Our approach is to recognize that Biology (Nature) itself can be viewed as an "engineered system" and that much of Biology's systems function (and dysfunction) at cellular (micro) and molecular (nano) scales. At these scales we explore a more formal "Mapping of Engineering onto Biology," for both health and disease, and new technological innovation. This defines our approach towards bioinspiration. Framing this approach, we recognize:

(1) Biology as a series of cellular products, nano-components, energy-consuming processes, and functioning devices that are "manufactured" with a limited set of materials, that nevertheless overcome the same physical and chemical limitations (force, temperature, pressure, E-fields, time, solubility, diffusion, etc.) as other inorganic materials, but do it to support life;

(2) disease, either due to defects in manufacturing, (genetic-based) or toxic insult (environmental-based), as an opportunity to detect and characterize what has changed compared to the "normal state";

(3) medicine, as a tool for prevention or cure, again at the gene-based manufacturing level, or by drug or biocompatible-prosthetic intervention.

This mapping framework is directed towards organizing and generating extensive information that at present is missing concerning the physical and chemical properties of cellular, intracellular, and membrane components that will lead to a greater understanding of how the molecular machines that drive healthy processes are built and function.

From this knowledge, we can then understand failures in these components that lead to disease or gain inspiration in the design of new materials and devices for humanity. Such an approach places existing (and future) knowledge, especially of cell and molecular biology, fairly and squarely in the realm of engineering materials and design methodology. It is, then, a formal Engineering Design Methodology, and a better understanding of the complex relationships between cellular and molecular material's composition, structure, properties and performance (CSPP), that is the cornerstone of our reverse and forward engineering exercises – motivated by basic questions in the biological sciences.

The Center for Biologically Inspired Materials and Material Systems at Duke University was founded to establish an integrative educational and research environment for students, faculty, and staff. The structure of the Center, mechanisms for fostering research and collaborative educational activities, and a few examples of results from these efforts will be discussed

Daltorio, Kathryn[1], Terence E. Wei[1], Stanislav N. Gorb[2], Jason M. Funt[1] Roy E. Ritzmann[1], and Roger D. Quinn[1] . *Enhancing Robotic Mobility Through Insect Strategies*
1 Case Western Reserve University
2 Max-Planck-Institute for Metals Research

Abstract. The biologically-inspired robotics group at Case Western Reserve University incorporates biological principles of locomotion into mobile robots. In this research, Mini-Whegs(TM), a 100-gram robot with a single propulsion motor, was adapted for the purposes of testing various climbing mechanisms. When climbing, insects utilize claws, tarsal spines and tarsal pads to create attachment forces. Having multiple gripping devices allows them to climb on a variety of surfaces, including those that are smooth, soft, or porous. For walking on hard smooth surfaces, insects use a series of tarsal pads which they sequentially detach. Similarly, the wheel-legs of the robot peel their adhesive feet from the substrate gradually, reducing the required torque. Using adhesive feet created from Scotch(R) tape, the robot is not only able to transition onto and walk up a vertical glass surface, but it is also able to walk inverted on the underside of a horizontal glass surface. The adhesive tarsal pads of geckos and some insects rely on dense arrays of setae or hairs. The setae are able to conform to microscopic roughness which increases the real contact area, allowing the animal to walk on vertical and inverted surfaces. We are using a polymer adhesive inspired by these structures that utilizes dense arrays of microscopic structures. This gecko-inspired material lasts about twice as long as Scotch(R) tape and allows the robot to walk up a vertical glass surface. Claws and tarsal spines can hook onto any surface asperities on porous substrates, or dig into soft substrates. The addition of a compliant ankle and tarsal spines to each foot has enabled Mini-Whegs(TM) 7 to climb a 60 degree incline at over 4 cm/sec, as well as steeper surfaces at slower speeds. A robot with spines and adhesive pads integrated on its feet has the potential for scaling a wide variety of surfaces

Program Guide and Abstracts

Full, Robert J. *Galloping Ghosts, Gripping Geckos and Bipedal Bugs: Bio-Inspired Robots, Adhesives and Artificial Muscles*
University of California Berkeley

Abstract. We define biological inspiration as the use of principles and analogies from biology when advantageous to generate novel designs through integration with the best human engineering. Our biological inspiration derives from Bio-motion. Our PolyPEDAL (Performance Energetics and Dynamics of Animal Locomotion) Laboratory uses the remarkable diversity in nature to lead to the discovery of general principles. Animals are amazing at legged locomotion because they have simple control systems, multifunctional actuators and feet that allow no surface to be an obstacle. Extraordinarily diverse animals show the same dynamics - legged animals appear to bounce like people on pogo sticks. Force patterns produced by six-legged insects are the same as those produced by trotting eight-legged crabs, four-legged dogs and even running humans. Rapid running cockroaches can become bipedal as they take 50 steps in a single second and ghost crabs seem to glide at 4 m/s with aerial phases. Yet, the advantage of many legs and sprawled posture appears to be in stability. Collaboration with mathematicians at Princeton has shown that these designs self-stabilize to perturbations without a brain or its equivalent. Control algorithms appear embedded in the form of the animal itself. Shape deposition manufacturing developed at Stanford has allowed engineers to tune legs of a six-legged robot, named SPRAWL, so that it self-stabilizes to perturbations without any active sensing. The principles of legged dynamics have inspired UPenn and Boston Dynamics to build the most mobile robot yet available, a hexapod named RHex. Our studies of cockroach muscle have shown that muscles operating at the same joint activated with the same neural signal can function as motors, springs, struts or shocks. This multi-functionality has inspired SRI and AMI to develop electroactive polymers that function as artificial muscles. Our study of amazing feet in creatures such as geckos has found that they climb up walls at over 1 m/s without using glue, suction or Velcro. Hairy toes allow adhesion using intermolecular forces. These discoveries are inspiring the manufacture of the first, self-clearing fibrillar adhesive by engineering collaborators at Berkeley and elsewhere. Clearly, cutting-edge research now requires an interdisciplinary approach. To train next generation of scientists, we are opening a new center (Center for Interdisciplinary Biological Inspiration in Education and Research - CIBER) with a common laboratory focusing on integrative biomechanics, but sharing the approaches to interdisciplinary biological inspiration in both education and research to the general community.

Gorb, Stanislav. Locomotory *Attachment Devices in Animals: Mechanisms and Biomimetic Implications*
Evolutionary Biomaterials Group, Max Planck Institute for Metals Research

Abstract. Most recent data on biological hairy attachment systems demonstrated their excellent adhesion and high reliability of contact. In contrast to smooth systems, some hairy systems seem to operate because of "dry adhesion", because they do not produce supplementary fluids in the contact area. Interestingly, hairy systems appeared several times in animal evolution and at least three times independently even within insect evolution. This fact may indicate that such a design of surfaces must have an advantage for adhesion enhancement not only in biological systems but also on artificial surfaces. The physical background of this effect was theoretically discussed in several recent publications. Comparison of the wide variety of animal groups revealed that the size of single contacting points gets smaller and their density increases as the body mass increases. This general trend is theoretically explained by applying the JKR theory, according to which splitting up the contact into finer sub-contacts increases adhesion. The effective elastic modulus of the fiber arrays is very small, which is of fundamental importance for adhesion on smooth and rough substrata. It is predicted that an additional advantage of patterned surfaces is the reliability of contact on various surface profiles and the increased tolerance of defects at individual contacts. In a real situation, failure of some mi-cro- contacts due to dust particles or to mechanical damage of single seta would minimally influence adhesion. In the case of a solitary contact, even slight damage of the con-tact due to the presence of dirt or surface irregularities will immediately lead to contact breakage similar to the crack propagation in bulk material. These theoretical considerations were only recently proven experimentally. Previously we have shown that structured surfaces have an increased tenacity (adhesion per unit of the real contact area). This effect was even stronger on the curved substrata. In the present study, adhesion of the structured surface on a smooth glass surface was compared with the adhesion of a flat sample made out of the same bulk material. Here we show that adhesion per unit of apparent contact area is also enhanced by multiplying of the number of contacts.

Grasso, Frank. *Modeling Octopus Suckers*
Department of Psychology, Brooklyn College, CUNY

Abstract. Octopus arms house dozens of independently controlled suckers that can alternatively afford an octopus fine manipulation of small objects and high force adhesion to a wide variety of non-porous surfaces. They can grasp, rotate and reposition soft objects like octopus eggs without damaging them and provide adhesion forces to anchor the octopus to a rocky substrate in the inter-tidal zone during wave surge. The biological "design" by which this is achieved is understood to be anatomically divided into three functional muscle groups: the infundibulum which produces a surface seal that conforms to arbitrary surface geometry; the acetabulum which generates negative pressures for adhesion; and the extrinsic muscles which allow adhered objects or surfaces to be rotated relative to the arm. The underlying physiological unit which makes this possible is the muscular hydrostat, which dynamically supplies force and mechanical stiffness as needed under direct neural control.

With appropriate sensory feedback to suit the situation, thousands of MHUs in the sucker act in coordination to make appropriate local changes in the geometry and stiffness of the sucker. The extreme malleability of octopus suckers and the fluidity of the interconnections of the infundibulum, acetabulum and extrinsic muscles make direct studies of the dynamics and control suckers extremely challenging. We have developed a simulator (ABSAMS) which models the essential functional units of the octopus sucker from biologically constrained muscular hydrostat models and connective tissue. These simulations are competent to quantitatively reproduce aspects of octopus sucker performance and squid tentacle extension. Simulations run with these models using parameters from man-made actuators and materials can serve as tools for designing soft robotic implementations of man-made artificial suckers and soft manipulators. The research reported here was supported by DARPA DSO BioDynotics Program (Subcontract 882-7558-203-2004599) Program Officer: Morley Stone

Program Guide and Abstracts

Gupta, Satyandra. *Using Biologically Inspired Robots as Case Studies for Teaching Bio-Inspired Product Development*
University of Maryland.

Abstract. Engineers have discovered that designs in the natural world can be successfully exploited to create engineered artifacts. However, existing mechanical engineering curriculums do not cover bio-inspired product development. Our prior curriculum development experiences indicate that in order to effectively teach bio-inspired product development, we will need to utilize rich design case studies that can motivate students. We believe that bio-inspired robots can serve as an excellent source of case studies for teaching bio-inspired product development.

This paper describes the newly developed bio-inspired robotics course at the University of Maryland. This course discusses the design of biologically inspired robots and their constituent technologies, namely sensors and actuators. The course begins with a look at how bio-inspiration can be used to develop a new class of mobile robots. Initially, an overview of robots is given and the motivation for bio-inspiration in mobile robot design is explained. Some of the questions being explored are "What can nature offer engineers?" and "Can bio-inspired designs outperform traditional technology?" The next matter that is discussed is how engineers can quantify and evaluate nature in order to select the animal that best meets a set of design requirements. Finally, several examples of bio-inspired mobile robots are shown in detail, including the motivation and bio-inspiration for their design, as well as technical specifications and comparisons to conventional mobile robots. The next portion of the course discusses biologically inspired sensing technologies that are widely used in bio-inspired robot applications. First, an overview of sensors is given, followed by a look at biological sensing and what nature's sensors are capable of achieving. Different types of next-generation bio-inspired sensors are then discussed in detail, including the motivation for their design and a comparison to the biological sensor that was the inspiration. The examples include a chemo-optical sensor, flow sensor, strain sensor, and many sensors used in the navigation of flying robots, such as optic flow sensors, gyroscopic sensors, and sonar. The final portion of this course is on biologically inspired actuators that seek to mimic the behavior of natural muscles, also known as artificial muscles. The structural hierarchy, basis of actuation, and actuation characteristics of biological muscle are discussed and then compared to traditional actuators that are used in various engineering applications, including robotics.

This course is intended to emphasize hands-on learning. As a part of the course projects, student teams have an opportunity to design and build their own snake-inspired or polypedal robots. These projects are expected to provide a very valuable design and manufacturing experience for mechanical engineering students. In addition to describing the course modules in detail, this paper also discusses our own experiences in designing and building snake-inspired robots.

Program Guide and Abstracts

Hartmann, Mitra J. *Novel Tactile Sensing Systems Inspired by the Rat Vibrissal*
Northwestern University

Abstract.Tactile sensing serves as a natural complement to vision because it can operate in the dark, underground, in fog, in the very near field of view, or when reflections and glare prevent accurate visual assessment of an object. Vibrissae (whiskers) are a particularly efficient method of encoding tactile information, and behavioral experiments have demonstrated that both rodents and pinnipeds can use their whiskers to navigate and extract environmental features without the use of vision. Specifically, rats use periodic 5-12 Hz whisker movements to extract an object's spatial properties, including size, shape, orientation and texture. Harbor seals use their whiskers to track the hydrodynamic trails of their prey.

Our laboratory has developed inexpensive arrays of artificial whiskers modeled after animal vibrissal systems that can be used either in active "whisking" mode or in passive "dragging" mode. The artificial vibrissae can determine obstacle distance, perform 3-dimensional extraction of object shape, and determine the velocity of a fluid flow. When used on a land-based mobile rover, such arrays could be used to map terrain features, determine ground and surface texture, provide an estimate of rover speed, and identify "slip" of the rover wheels. On an underwater vehicle, vibrissal arrays might be used to track wakes and characterize fluid flow.

To improve performance of the artificial whisker arrays, our laboratory has been quantifying the particular features of real rat whiskers that may uniquely enable different aspects of the sensing process. A detailed characterization of the geometry and mechanics of rat vibrissae has identified several properties that appear to hone their sensing capabilities. For example, the whisker's roughly-linear taper renders it particularly sensitive to vibrations at the tip, and particularly sensitive to static bending closer to the base. Because vibrations are important for texture extraction, while bending is important for object shape extraction, the differential sensitivity suggests that different segments of the whiskers may be optimized to acquire different types of sensory information. I will discuss possible methods for instantiating these types of differential sensitivities in the hardware arrays.

Large-scale head movements of the rat complement movements at the single-whisker level. We have developed a complete 3-dimensional model of the rat head and whiskers in order to predict the spatiotemporal patterns of activity across the vibrissal array as the rat is engaged in different exploratory tasks. We are interested in identifying exploratory procedures that optimally extract particular types of information, and in examining the tradeoffs between spatial and temporal resolution.

Finally, I will discuss how the artificial whisker arrays can serve as an investigative tool for exploring the neurobiological encoding of sensory information. Results from our hardware models have allowed us to make strong predictions about the neural encoding and processing that must occur in order for the rat to interpret incoming sensory data. In other words, we can infer how the brain is likely to process data from mechanical analysis. Hardware models are becoming increasingly essential in understanding the ways in which biological sensing mechanisms and movement control strategies are interlocked.

Hildebrand, Mark and Aubrey K. Davis. *Structural Control, Molecular Components, and Multi-level Regulation of Biosilicification Diatoms*
Scripps Institution of Oceanography

Abstract. The unicellular algae known as diatoms produce cell walls containing complex three-dimensional nano- and micro- scale silica structures, with a complexity and organization exceeding that possible with current synthetic nanostructured silica syntheses. Because these diatom structures are reproduced inexpensively with fidelity, and in enormous numbers through biological replication, they are being considered as a source of materials for nanotechnology. Diatom silica structure formation occurs by a fundamentally different mechanism than used in current synthetic approaches, because it does not rely solely on an internal or pre-structured template or repetitive self assembly, but rather occurs dynamically inside an expandable and moldable membrane-bound intracellular compartment called the silica deposition vesicle, with control occurring at multiple levels. To elucidate processes involved in diatom silica structure formation, our research is aimed at 1) identifying structural intermediates during formation, 2) identifying and characterizing molecular components involved and correlating their involvement with formation of specific aspects of structure, and 3) elucidating the regulation and interplay of components involved. We are focused on studying *Thalassiosira pseudonana*, the first diatom with a complete genome sequence, which enables the application of powerful genomic and proteomic approaches. We recently completed an examination of structural intermediates in cell wall formation in *T. pseudonana* and identified three scales of structure formation and organization. Distinct silica morphologies were observed in different structures, and these morphologies correlated with optimal design properties for the final product. Our development of synchronized culture procedures for *T. pseudonana* has enabled monitoring gene expression (as changes in mRNA levels) during formation of specific cell wall structures, and coupled with the identification of silica polymerizing proteins known as silaffins by Poulsen and Kröger (JBC 279:42993, 2004) we have for the first time made a connection between structural, molecular, and biochemical processes in diatom silicification. In ongoing work to identify other components of the silicifying machinery we have used proteomic and whole genome microarray approaches, resulting in identification of novel genes with expression patterns similar to the silaffins. A clearer picture of cellular pathways and processes involved in silicification will emerge as more cellular components are identified. Diatom silica structure is ultimately genetically based; however proper structure formation must involve an integrated cellular system that includes regulatory steps in gene expression (including intracellular targeting and post-translational modification) and temporally and spatially coordinated interaction between components. Development of genetic manipulation approaches will enable perturbation of the system at various levels, and aid in identifying the function of genes, particularly novel genes. Such approaches will be essential to understand how diatom genetic information is translated into active chemical moieties that ultimately control the formation of a solid material. Comprehensive understanding will also facilitate genetic and other manipulations to generate materials with tailored structures for specific nanotechnological applications.

Hulsey, C. Darrin, Richard Roberts, J. Todd Streelman. Georgia Institute of Technology, School of Biology, Atlanta, GA, 30332,
USA. *Adaptive Evolution of Universal Testing Machines: Integrating Micro CT, FEA, and Jaw Strength in Cichlid Fishes*

Abstract:
The pharyngeal jaw of cichlid fishes may represent a key innovation that facilitated their extensive exploitation of durable prey such as mollusks. To examine characteristics of the lower pharyngeal jaw that may enhance the ability of cichlids to exploit durable prey, 3D computed microtomography (micro-CT) scans were used to examine the external and internal structure of the lower pharyngeal jaw of 11 Heroine cichlids from Central America. We CT-scanned the LPJ in both the molluskivorous and non-molluskivorous alternative morphotypes in the polymorphic cichlid *Herichthys minckleyi*. We also examined the LPJ in five independent evolutionary contrasts between species that differ in the extent to which they crush mollusks. Differences in the extent of internal suturing, size of the horns that serve as muscular attachment sites, keel size, erupted tooth size, replacement tooth size, and depth of tooth crypts will be discussed using these contrasts. We assessed the extent of convergence among the durophagous species in these traits. Finally, using Finite Element Analysis we also determined in silico the contribution of these morphological elements to resisting forces encountered during mollusk crushing.

Program Guide and Abstracts

Kamal, Firdous[1], Diane Ramos[2], Alexander N. Cartwright[1], Antonia Monteiro[2].
1 Department of Electrical Engineering, University at Buffalo, Buffalo, NY
2 Department of Biological Sciences, University at Buffalo, Buffalo, NY

Laser-induced gene expression in live transgenic butterflies in a controlled spatial and temporal fashion

Abstract. The use of transgenic animals has allowed major advances in the field of functional genetics, but only a hand full of model organisms are currently being used for these studies. The genomes of these organisms have usually been fully sequenced and regulatory DNA sequences that drive gene expression in particular patterns is already fairly well understood. In order to open the field of functional genomics to non-model organisms with little or no regulatory sequence data, we have developed a new laser heat-shocking technique that provides precise temporal and spatial control of gene expression without requiring knowledge of enhancer sequence data. We are testing this system by exploring the role of various candidate genes in the development of butterfly wing patterns to better understand how morphological novelties are generated over the course of evolution. We tested our laser-system in a transgenic line of *Bicyclus anynana* butterflies containing the EGFP reporter ge ne attached to the heat-shock promoter of Hsp70 of *Drosophila melanogaster*. This promoter acts as a heat switch for the attached reporter gene as cell temperature is increased. Whole body heat shocks previously showed that this Drosophila promoter can drive gene expression in butterflies, and laser heat-shocks now show that it is possible to activate cell-specific gene expression in very precise patterns on the developing wing. Various laser wavelengths of 488, 514, 1100 and 1460 nm were tested and will be discussed in regard to performance, cell damage, and animal survivability

Program Guide and Abstracts

Koehler, Stephan. How to swim in sand.
Department of Physics, Emory University

Abstract. The Western shovel-nosed snake (*Chionactis*) has the ability to ``swim'' beneath surface of the Sonoran desert surface with little effort, but the mechanics of how this and other desert organisms propel themselves through the using an undulatory motion are poorly understood. In general, swimming is the consequence of a balance of the torques and forces generated by the swimmer's motion and the media's resistive drag. Swimming has been studied by applying Navier-Stokes' equations to a plethora of organisms ranging from the smallest single-celled bacterium to the largest whale. In contrast, no equations for granular flow exist, thus it is unknown how animals are able to swim in granular media. Here we use a robotic mechanism with two rotating paddles as an experimental model system to elucidate the forces generated by motion in granular media and compare swimming in viscous fluids to swimming in granular media. We determine the effect of paddle size, stroking angle, and stroking sequence on the robot's locomotion. For a symmetric stroking sequence the robot's translation resembles that of its viscous counterpart in terms of the direction and the magnitude of the displacement. However, for an asymmetric stroking sequence the motion of the robot is opposite to that of its viscous counterpart. Furthermore the experimental results may serve as a new benchmark for testing granular theories. Practical applications include robotic exploration beneath the desert's surface and traversing loose granular media where vehicle wheels of often spin without traction. For example NASA's rover "Opportunity" was stuck in a Martian sand dune for several weeks. The approach of this study can be extended to self-propulsion in other fluid-like environments, such as miniaturized robots swimming through the vascular or digestive systems for novel, non-surgical therapeutic procedures.

Kotas, C. W, Minami Yoda, and Peter H. Rogers. *Acoustically Induced Flows in the Fish Ear*
School of Mechanical Engineering, Georgia Institute of Technology

Abstract. Teleosts, or bony fish, are capable of determining the direction and range of underwater sound at frequencies of 10–1000 Hz and wavelengths of 1.5–150 m within 10° using two passive sensors spaced a few centimeters apart: their ears. These ears contain irregularly shaped, dense, bony otoliths that, when exposed to sound, oscillate with respect to the surrounding tissue and fluid. This oscillation bends the ciliae of the hair cells adjacent to the otolith, and the displacements of these ciliae are effectively what fish "hear." Understanding the acoustically induced fluid flows inside the fish ear due to incident sound, specifically near the otolith, may give insights on how fish localize underwater sound sources and lead to compact, directionally sensitive underwater acoustic sensors. The time-independent component of these acoustically induced flows, *i.e.*, steady streaming, was studied for sinusoidally oscillated spheroids of various aspect ratios using flow visualization and particle-image velocimetry (PIV). The extent of the inner flow region (of primary interest in sensing application) appears to scale with the inverse of the flow Reynolds number for a body length scale defined as the product of the spheroid aspect ratio and its equivalent radius. The effect of sound direction on the flow patterns in the inner region was investigated by studying steady streaming around spheroids oscillated at various angles with respect to the axis of symmetry.

Kotas, C. W, Minami Yoda, and Peter H. Rogers. *Visualizations of Steady Streaming Flows: Could Fish Ears Be "Auditory Retina"?*
School of Mechanical Engineering, Georgia Institute of Technology

Abstract. Acoustically induced oscillatory flows in the fluid (endolymph) and tissue of fish ears have a time-independent component due to nonlinear effects. This "steady streaming" flow is capable of generating complex flow patterns between the otolith and macular membrane that contains information about incident sound properties. The "auditory retina" hypothesis suggests that such flow patterns are sensed by the large number of macular hair cells, much like how photoreceptors on the (visual) retina sense patterns of light. To investigate this hypothesis, steady streaming around model otoliths, here represented by spheroids of various aspect ratios, was visualized using phase-averaged particle pathlines. Estimates of the extent of the inner region of this flow imply that the results for several different spheroid geometries are consistent for a body length scale defined as the product of the spheroid aspect ratio and equivalent radius, and that this extent scales as the inverse of the Reynolds number. To study the directional sensitivity of these flow patterns, steady streaming was studied around spheroids oscillated obliquely, or at a nonzero angle with respect to its axis of symmetry. This oblique oscillation has marked effects on the flow patterns.

Program Guide and Abstracts

Lauder, George. *Biodesign for Aquatic Propulsion: Fish Fins as Flexible Thrusters*
Harvard University

Abstract. There are 28,000 species of fishes, and a key feature of this remarkable evolutionary diversity is the great variety of propulsive systems used by fishes for maneuvering in the aquatic environment. Fishes are noted for their ability to maneuver and position themselves accurately even in turbulent flows, and this ability is the result of the coordinated movement of fins which form flexible control surfaces that allow thrust vectoring. Fishes have numerous control surfaces which act to transfer momentum to the surrounding fluid, and fishes are designed to be unstable and to use several control surfaces simultaneously for propulsion and maintenance of body position.

Fish are thus natural subjects to use for inspiration in designing the next generation of autonomous underwater vehicles (AUV's) for aquatic exploration. Such fish-inspired AUVs will utilize flexible fin-inspired propulsors (rather than propellers) that minimize noise and provide enhanced maneuvering capabilities compared to current designs.

I will summarize the results from our collaborative research program which is designed to understand the dynamics of fin function in fishes and to construct a biomimetic robotic fin thruster. We first quantified the motion of sunfish fins during both propulsion and maneuvering in three dimensions using multiple high resolution high-speed digital video cameras. Kinematic analysis shows that during steady propulsion the sunfish fin is deformed considerably in both chordwise and spanwise directions. Fish fins are highly flexible propulsors, and have a unique bilaminar design with muscular control that permits fish to actively modulate fin surface curvature and to resist hydrodynamic loading. We have used digital particle image velocimetry (DPIV) on the fins of freely swimming fishes to image flow, and computational fluid dynamics (CFD) to calculate flows based on measured 3D kinematic data. DPIV experiments show that during the fin beat, the fin has two leading edges with two simultaneous attached leading edge vortices present as the fin cups laterally during the outstroke. Both DPIV and CFD data demonstrate that the fin generates thrust throughout the fin beat with two distinct thrust peaks. Fish fin flexibility greatly reduces the magnitudes of side and vertical forces as compared to more traditional engineering heaving and pitching foils, and results in increased propulsive efficiency. Fin flexibility also allows at least some parts of the fin to produce thrust at all times. Active reorientation of the fin base allows thrust vectoring during maneuvering.

A first generation robotic model of the sunfish pectoral fin has been developed that can reproduce key aspects of the complex pectoral fin motion.

Liu, Chang[1], Joseph Humphrey[2], Sheryl Coombs[3], Douglas Jones[4], Vladimir Tsukruk[5].
Artificial Haircell and Artificial Lateral Line Sensors: Design, Material, and Application
1 University of Illinois, 2 University of Virginia, 3 Bowling Green University, 4 University of Illinois, 5 Iowa State University

Abstract: Biological sensors are responsible for the survival of humans and animals in complex, unstructured environments. As such, these sensors possess superb combination of sensitivity, robustness, and efficiency of data processing. There are many things to be learned from biological sensory functions, structures, materials, and perception. Advancements in microfabrication and nanofabrication make mimicking such functions and structures feasible today. We are developing artificial haircell sensors that mimics the biological haircell or hair-like receptors that are used in wide range of functions including hearing, balancing, touch, vibration- and flow sensing. We are also developing artificial lateral line sensors, consisting of an array of flow-sensing artificial haircell sensors. The artificial lateral line sensor mimics the lateral organ of fish and amphibian animals, which are useful for forming images of water flow and instrumental in controlling underwater movement. In this talk, we will discuss the design of several generations of haircell sensors, along with the advancement of polymer MEMS technology and sensor-circuit integration. This effort is a global collaboration between biologists and engineers to advance understanding of biology, applying biological findings in engineering practices, and building advanced engineering sensors and sensor-rich systems. Artificial haircell sensors have been building using silicon as well as organic polymers (including conductive elastomer and polyimide). The sensors have been designed and tested as flow sensors. The sensitivity has been enhanced by 100 fold through the use of hydrogel decoration. Artificial lateral line sensors have been successfully tested. They can detect the location and trajectory of a traveling oscillating dipole source in water.

Lu, Hang *What we can learn from a worm's brain*
Department of Chemical and Biomolecular Engineering, Georgia Inst. Technology

Abstract. *C. elegans* is a free-living soil nematode with exactly 302 neurons.Despite of the simple nervous system*, C. elegans* senses touch, smell taste, and temperature; it is capable of finding mates and escaping predators; it even demonstrates forms of learning and social behavior. We are interested in how *C. elegans* neural circuitry evolves to become efficient in sensing its environment and produce the correct behavior. Specifically, we are studying different spatial and temporal sensing mechanisms by which *C. elegans* locates food (bacteria) using oxygen as a cue. What mechanisms are most efficient? What mechanisms are most flexible? When should they use these mechanisms or a combination of these mechanisms? We are trying to address some of these questions by using engineered micro devices in combination with laser ablation of single neurons.

Luckarift[1,2], Heather, Lorena Betancor [1,2], Cecile Berne[1,2], and Jim Spain[2]. *Enzyme immobilization by silification reactions*
1 Air Force Research Laboratory, Tyndall AFB,
2 School of Civil and Environmental Engineering, Georgia Institute of Technology

Abstract: Enzyme immobilization provides a versatile physicochemical tool that allows the reuse or continuous use of enzymes, facilitates substrate and product recovery, prevents product contamination and in certain instances, improves the properties of the biocatalyst. Silaffin polypeptides from diatoms catalyze the formation of 'bio'silica via biosilicification; a reaction that occurs in vitro at neutral pH and ambient temperature and pressure. The silica-precipitating peptides become entrapped during the generation of the silica matrix leading us to investigate the use of the biosilicification reaction for the entrapment of exogenously added enzyme in a silica matrix. Here we show that several enzymes with varying structural complexity could be successfully immobilized using the biosilica entrapment method. Immobilized preparations not only retained activity but also proved more stable than the soluble enzyme in a wide variety of conditions. We also explored the use of low cost alternative agents for the silica precipitation reaction. The resulting silica-encapsulated/enzyme nanospheres exhibit mechanical properties that proved suitable for continuous operation in a flow-through reactor. The use of biosilica for enzyme immobilization offers a widely applicable and versatile immobilization tool and provides the basis for a range of potential applications using silica-encapsulated enzymes.

McHenry, M.J.[1], S.M. van Netten[2]. *Flexible flow filters in fish: the mechanics of hydrodynamic reception*
1 U.C. Irvine, 2 Univ. of Groningen

Abstract: Fish detect water flow with an array of receptors that are collectively known as the lateral line system. We explored the mechanics of the receptors on the surface of the skin, known as superficial neuromasts (SN), in order to understand how they filter hydrodynamic signals in larval zebrafish (*Danio rerio*). These mechanics were examined with a combination of morphological measurements, stiffness measurements, and mathematical modeling. SNs are composed of a transparant gelatinous matrix that is anchored to the body by 4 to 16 mechanosensory hair cells. Using a novel visualization technique, we found that the cupula maintains a tapered cylindrical shape along its height and that this tapering increases above the tips of the kinocilia of the hair cells. This finger-shaped structure has a diameter of approximately 10 µm at its base, extends about 40 µm from the surface of the body, and contains the kinocilia of between 4 and 16 hair cells. Cantilever bending tests found the Youngs Modulus of the SN to be around 100 Pa, which is a range comparable to that of mucus. Mathematical modeling suggests that the elongated geometry and flexible material of the SN cause these receptors to bend when exposed to the hydrodynamic loads typical of swimming fish. Therefore, the beam dynamics of the SN play an important role in how hydrodynamic signals are filtered by the lateral line system.

Migliore, Shane, Edgar A. Brown, Stephen P. DeWeerth. *Biomimetic Actuators for the Control of Robot Joint Complianc*e
Georgia Tech Laboratory for NeuroEngineering

Abstract. Robotic joints with variable compliance are able to adapt to varying task requirements and can take advantage of natural limb and joint dynamics. The implementation of controllable compliance in robots, however, is often constrained by the inherent instability of active compliance methods and by the limited availability of the custom, nonlinear springs needed by passive compliance methods. This work overcomes a major limitation of passive compliance by producing designs for two novel mechanisms capable of generating a wide variety of specifiable, nonlinear elastic relationships. One of these designs is physically implemented as a quadratic "spring" and is used to create a passively compliant robot joint with antagonistic series-elastic actuation. A simple feed-forward algorithm is then experimentally shown to be sufficient to control independently and simultaneously both joint angle and joint compliance, regardless of the presence of external loads. We believe that this is the first physically constructed system to use antagonistic quadratic springs to successfully demonstrate open-loop, independent, and simultaneous control of both joint angle and joint stiffness. Because this approach better emulates the underlying joint mechanics used by animals, it may improve both the quality and variety of robotic movements

Müller, Rolf *Biosonar-Inspired Design - Past, Presence,Future*
Shandong University.

Abstract. Biosonar is a sophisticated far sense which meets the sensory needs resulting from a diverse set of highly mobile predatory lifestyles seen in bats. Even before its exact physical nature was discovered, biosonar had been recognized as a source of inspiration in the technical areas of sonar and radar sensing. Over the last 15 years, robotic implementations have been used successfully to study certain aspects of biosonar function such as target tracking, dynamic estimation of target elevation, fast adaptive focusing, as well as classification of deterministic and random targets. To perform these tasks, the technical embodiments have replicated various functional aspects of biosonar including sensor mobility (translations and rotations), beamforming baffles, and signal encoding with a sparse spike code. At the same time, biosonar has been mimicked to devise mobility aids for the blind.

The fundamental problems which biosonar systems address are shared with a large set of sensing and communication applications which go far beyond sonar/radar and ultrasonic mobility aids for the blind. Therefore, biosonar has the potential to inspire novel technical solutions in application areas which are not obviously related to it by physical nature or sensing task. Examples of fundamental signal processing and estimation operations relevant to biosonar and a wide range of technical systems are fast estimation of channel properties and adaptive beamforming. Both are important to such fields as wireless communication, non-invasive biomedical diagnostic techniques, as well as non-destructive testing and monitoring. Biosonar beamforming offers a convenient model system for the study of the relationship between form and function. Because the shape of a beamforming baffle for ultrasound in air determines its properties, a high-resolution representation of these shapes in bats (i.e., noses and ears) is sufficient to deduce its function from the morphology.

Two research directions seem particularly promising for future work in biologically-inspired design: the study of novel functional principles not used in technical applications so far and the automation of the design process. In biosonar, many novel functional properties remain to be studied and investigated for their technological relevance, for example deformations of beamforming baffles (noses and pinnae) and the adaptive use of non-stationary signals. The automation of the design process poses a fundamental challenge to biologically-inspired design in the same way as to any other area of technology design. Automation is desirable because it makes customized solutions available to a wider range of applications. At present, biologically-inspired design relies on the analysis of individual natural systems, which is laborious and may fail to yield a good paragon. The diversity among the biosonar systems of the more than 1,000 bat species worldwide offers an opportunity to address this issue: The solution space spanned by their biosonar systems can be characterized by analyzing the natural variability in morphology and function. The resulting design rules can be used to find an optimum inside this space for any technical application regardless of whether this optimum is actually also exploited in nature or not.

Pulido, Gonzalo. *Biomimetics: Breathing Skin.* Florida International University

Abstract: "Emergence Architecture" intended as the application of Biomimetics theories to architecture, does not pertain merely to the built structure, but also to its environment, human necessities, and physical matter. This project, a skyscraper, is developed using emergences to design a more efficient building responding to its direct environment.

The scheme focuses on skin, functioning both as structure and element of climate protection. The design investigation of a structural skin as reaction (movement) originated from the site climate characteristics. The main factor, therefore, becomes adaptation for energetic self sufficiency. This high-rise reacts to the specific environmental conditions of tropical Miami. Its skin design evolved from studies of local wind pressure measured at extreme height conditions, and from the necessity to ventilate interior spaces to remove excess humidity. This skin further allows for the effective manipulation of natural light, temperature and interior lighting.

The building skin is composed of two layers: a breathing layer on the outer building edges and a less permeable layer on its inside. The external layer is generated by the opposite spinning of two spirals generating rhomboid shapes forming a hyperboloid parabolic. These individual cells are operable and are composed of two layers of different membranes. The computer controlled position of these two external skin membranes allow for the manipulation of light, wind and heat. One membrane is provided with solar cells. The living spaces between the two building skin layers become channels of ventilation for the whole building and common green space filters.

Rutter, Brandon[1], Laiyong Mu[2], Roger D. Quinn[1], Roy E. Ritzmann[2]. *A Model that Transforms Insect Electromyograms into Pneumatic Muscle Control*
1 Department of Mechanical and Aerospace Engineering, Case Western Reserve University
2 Department of Biology, Case Western Reserve University

Abstract. Robots can serve as hardware models for testing biological hypotheses. Both for this reason and to improve the state of the art of robotics, we strive to incorporate biological principles of insect locomotion into robotic designs. Previous research has resulted in a line of robots with leg designs based on walking and climbing movements of the cockroach Blaberus discoidalis. The current version, Robot V, uses muscle-like Braided Pneumatic Actuators (BPAs). In this paper, we use recorded electromyograms (EMGs) to drive robot joint motion. A muscle activation model was developed that transforms EMGs recorded from behaving cockroaches into appropriate commands for the robot. The transform is implemented by multiplying the EMG by an input gain thus generating an input pressure signal, which is used to drive a one-way closed loop pressure controller. The actuator then can be modeled as a capacitance with input rectification. The actuator exhaust valve is given a leak rate, making the transform a leaky integrator for air pressure, which drives the output force of the actuator. We find parameters of this transform by minimizing the difference between the robot motion produced and that observed in the cockroach. Although we have not reproduced full-amplitude cockroach motion using this robot, results from evaluation on reduced-amplitude cockroach angle data strongly suggest that braided pneumatic actuators can be used as part of a physical model of a biological system

Rutkowski, Adam, Mark Willis and Roger Quinn. *Development of an Aerial Three-Dimensional Odor Tracking Strategy*
Case Western Reserve University

Abstract. Odor tracking strategies have gained importance with applications to seeking improvised explosive devices and hazardous materials. The approach taken here for developing an odor tracking strategy is to draw inspiration from the pheromone tracking behavior of the tobacco hornworm moth. A successful odor tracking algorithm depends on reliable determination of the wind direction. A method for determining the wind direction using a camera and airspeed sensors onboard an unmanned aerial vehicle was developed and tested in simulation. The absolute error between each component of the true and estimated wind velocity vector had a standard deviation of less than 0.065 m/s for a true wind velocity on the order of 1 m/s. A method of tracking an odor plume was then developed and tested in a separate simulation. The desired motion of the tracking vehicle was decomposed into a component tangential to the wind and a component normal to the wind. In this work, only the normal component of the velocity is controlled and the tracking vehicle remains at a constant distance downwind from the odor source. The turn rate of the normal component of the velocity vector is adjusted to keep the tracking vehicle near the odor plume. The odor tracking strategy directed the tracking vehicle to turn continuously around the odor source in a manner similar to the moths and was capable of adapting to different odor plume geometries.

Scrivens, Jevin[1], Lena Ting[1,2,] and Stephen DeWeerth[1]. *Scaling of Feedback Control Gain with Stance Width*
1 Department of Biomedical Engineering, Georgia Institute of Technology,
2 Emory University

Abstract. Using a robotic model of a cat, we are exploring the relationship between feedback control gain, neural delay, and mechanical stability. Our goal is to quantify the tradeoffs between mechanical and neural stabilization. We hypothesize that neural control gains must be increased to maintain stability under perturbation when stance width is reduced. By using this robotic system we will be able to observe and even modify parameters that are not observable in biological systems.

Our robot is a two-legged device with one degree of freedom per leg. It simulates the lateral motion of a cat through abduction/adduction of the hip/shoulder combination. Posture is maintained by a controller using delayed feedback of the kinematic variables. These delays are set to various physiological latencies.

By subjecting the device to lateral displacement perturbations, we quantified postural performance across a range of stance widths and control gain values. Performance was assessed by measuring movement, energy consumption, and control effort during the perturbation response. By performing optimizations to minimize these cost functions across stance widths, we identified optimal control gains for each stance width. Preliminary results indicate a 500% increase in required control gain as we decrease stance width by 53%. There is a significant decrease in neural control gain with wide stance. This correlates with experimental findings in cat and human postural responses where EMG decreases as stance width increases. Our results suggest that even a small increase in stance width can compensate for a decrease in neural control ability associated with motor impairments.

Shapiro, Arthur G.. *Counter-shading, camouflage, and the design of visual illusions*
Bucknell University

Abstract Many animals have a counter-shaded coloration (i.e., they have a dark dorsal region and light ventral region). Counter-shade patterns are often referred to as obliterative camouflage because, in the words of Abbott H. Thayer (the American painter who coined the term), such patterns "obliterate" the contrast between the animal and surround. While counter-shading has proven useful for concealment of military targets, the concept of obliterative camouflage has always been problematic: Why is countershading often paired with bright colors? What are the spatial for measures of contrast concealment? (etc.) Here, I will demonstrate that in addition to improving concealment, counter-shading may also serve to create false motion information, and that the basic principles underlying counter-shade motion can be used to design a new class of visual illusions (gradient-gradient illusions) that may have implications for many different types of design.

Counter-shade motion can be understood as arising from the same elemental principles as another class of compelling visual illusions referred to as single-field contrast asynchronies (Shapiro et al 2004ab, 2005). Single-field contrast asynchronies are defined by two features: 1) a single source of luminance modulation; and 2) multiple sources of contrast modulation that differ from each other in their relative temporal phases. So, for instance, consider a spatially uniform disk whose luminance level is modulated in time (between 1 and 3 Hz), surrounded by a static annulus, split so that half of it is light and the other half is dark. The physical contrast at the light edge modulates in antiphase relative to the physical contrast at the dark edge. When the split annulus is thick, the disk appears to be inhomogeneous, as if a window shade is being pulled back and forth across the disk. When the annulus is thin, or when a thin gray gap is inserted between the disk and the split annulus, the disk appears to move back and forth or up and down. I will demonstrate that a simple model based on the output of arrays of spatio-temporal filters can predict such motion. Many of the illusions can be viewed at www.shapirolab.net or at www.journalofvision.org/4/6/5 and www.journalofvision.org/5/10/2

Shian, Samuel, Ye Cai, Shawn Allan, Michael Weatherspoon, and Kenneth H. Sandhage
Syntheses of Nanostructured Ceramic Microparticles with Selectable Intricate 3-D Shapes and Tailored Chemistries via Bioclastic and Shape-preserving Inorganic Conversion (BaSIC).
School of Materials Science & Engineering, Georgia Institute of Technology, Atlanta, GA

While a number of powder synthesis routes can generate uniform ceramic particles of simple shape (e.g., spheres of similar diameter), the reproducible fabrication of ceramic microparticles with a selectable complex shape remains a difficult challenge. Impressive control over ceramic particle formation can, however, be found in nature. Certain micro-organisms generate microscopic inorganic shells with complex and highly-reproducible shapes. Perhaps the most diverse range of microshell shapes exists among the diatoms. Diatoms are single-celled algae that are ubiquitous to marine and freshwater environments. Each diatom species generates a silica-based microshell with a particular morphology. Reproduction of a given diatom species results in precise replication of the microshell morphology. Sustained biological reproduction (repeated doubling) can yield large quantities of microshells with the same shape. Indeed, the technology for large scale diatom culturing is well established (e.g., for providing planktonic diatoms as a food source in aquaculture operations). Furthermore, the estimated 100,000 diatom species currently on the planet provide an impressive range of microshell shapes from which to select for a desired powder morphology. However, the silica-based chemistry of diatom microshells is not appropriate for many ceramic powder applications.

The objective of this work is to understand how to change the chemistry of diatom microshells (and other bioclastic structures) into a variety of functional ceramics without altering the microshell shape. One approach taken is to expose the silica microshells to a reactive halide gas to allow for a metathetic displacement reaction of the following type: $TiF_4(g) + SiO_2(s) \Rightarrow TiO_2(s) + SiF_4(g)$ Under appropriate conditions, this type of exchange reaction can be used to generate chemically altered replicas (e.g., TiO_2 replicas) of the starting microshells. Shape-preserving inorganic conversion reactions have been utilized to convert silica-based diatom microshells into a number of functional ceramic compounds (MgO, CaO, TiO_2, ZrO_2, $BaTiO_3$, etc.). By combining large scale diatom culturing with such shape-preserving reactive conversion, ceramic powder particles with well-controlled, complex, and uniform shapes can be mass produced at low cost for a host of optical, electronic, medical, environmental, and structural applications.

Shu, Lily (Li) *Generalizing Biologically Inspired Design for Problem Solving*.
University of Toronto

Abstract. While many elegant solutions to engineering problems have been inspired by biological phenomena, it is not always clear how the particular biological phenomena were selected. This talk will present a generalized methodology by which analogous biological phenomena can be identified and used for any design problem in a systematic manner. To avoid the immense as well as potentially biased task of creating a database specifically for this purpose, the chosen approach searches biological knowledge in natural language format, e.g., books, papers, etc. Analogies for case studies in design for remanufacture and microassembly as well as ongoing work will be summarized.

Solga, Andreas, Zdenek Cerman, and Wilhelm Barthlott. *Lotus-Effect®: Biomimetic super-hydrophobic surfaces and their application*
Nees Institute for Biodiversity of Plants

Abstract. Important processes occur at the interfaces between organisms and their environment. This holds particularly for the plant cuticle. With the majority of plant species the cuticle is not smooth but microstructured; moreover, it is often covered with wax crystals in the dimension of some hundred nanometers. The combination of a coarse and a fine structure, together with a hydrophobic chemistry of the waxes, produces a fascinating phenomenon: Water on such surfaces forms spherical droplets whose contact angle exceeds 140 degrees by far. This behaviour is defined as super-hydrophobicity. Furthermore dirt particles cannot adhere to such surfaces because the contact area between them and the surface is extremely reduced. The particles are removed by running water only, hence the surface is able to clean itself. After the discovery and the analysis of the self-cleaning effect the mechanism was applied to first technical prototypes. The technical conversion was patented and the trade mark Lotus-Effect® was introduced. In the mid-1990s a large cooperation project with industrial partners started. Since then several Lotus-Effect® products have been marketed: a facade paint and a rendering by Sto AG, a coating for glass and metal surfaces by Ferro, a spray and a nano-particle powder (Aeroxide LE®) for multipurpose applications by Degussa. A recent project focused on the question whether the self-cleaning properties of Lotus-Effect® surfaces also protect buildings from biodegradation. The project included development of a standard method for comparing conventional building surfaces and biomimetic Lotus-Effect® surfaces with regard to mould and algae infestation. In 2005 a new project linked with Lotus-Effect® got under way. It focuses on floating plants and semiaquatic animals which have surface structures retaining an air film under water. A first textile prototype based on the principles of these structures has already been developed. A major target of this project is to develop surfaces that create stable underwater air films. Such films may result in significant drag reduction and, if applied in ship building, yield considerable savings in fuel

Summers, Adam P. *Interesting properties of cartilaginous skeletons*
UC Irvine

Abstract: The skeleton of sharks skates and rays is composed of a tiled ceramic layer over a viscoelastic core. The architecture of this composite material shifts the tensile component of bending to the compressed side. Furthermore the viscoelastic central core is a gel whose material properties vary within the narrow range of temperatures that is biologically relevant for this group.

Sundar, Kartik[1], Lena H. Ting,[1,2] and Stephen P. DeWeerth[1] *Nonlinear Intrinsic Muscle Stiffness and Damping as an Effective Autonomous Controller*
1 Georgia Institute of Technology, Department of Biomedical Engineering
2 Emory University

Abstract. The animal neuromuscular system provides an elegant solution for a robust control architecture. We believe that robotic actuators and controllers that act like muscle are a favorable design for autonomous stability. We are interested in studying the interactions between the mechanical properties of muscle and descending neural control during postural stability. Since neural feedback control has long destabilizing time delays, we propose that the intrinsic properties of muscle reduce neural control effort and simplify the neural control architecture. Experimental data suggest that the nonlinearities in intrinsic muscle stiffness and damping help stabilize perturbations. These experiments, however, fail to assign the muscle to a functional task such as joint stabilization. We designed and built a hybrid neuromechanical joint that allows an in vitro frog gastrocnemius muscle to actuate a computational joint. We hypothesize that intrinsic muscle stiffness and damping vary during a perturbation response, and that this variation leads to improved joint stability. An inverted pendulum was used as an unstable computational joint model and we applied a series of torque impulses to the joint that varied in magnitude and direction. Settling time was measured to quantify stability. We computed the muscle stiffness and damping during the stabilizing trajectory of each perturbation. Perturbations to the joint resulted in stable damped oscillations. We also found that the damping and stiffness of the in vitro muscle varied in an oscillatory manner. These nonlinear changes in damping and stiffness reduced settling time. As a result of these findings, we believe that the mechanical properties of intrinsic muscle serve as an autonomous joint controller.

Program Guide and Abstracts

Swackhamer, Marc. *Biomimicry: Nature as Model, Mentor, and Measure*
College of Architecture and Landscape Architecture, University of Minnesota

Abstract. In this graduate level studio, we engage a series of open-ended questions about the relationship between our natural and built environments. What can biological systems in the midst of millions of years of slow evolution teach us about the ways in which we design, construct, transport, market, maintain, use, and discard our built inhabitations? How can we learn about and be inspired by not just the beautiful forms we observe in biology, but by the way natural systems operate and perform? Can architecture be grown? Can it respond to its environment in real time, without constant monitoring? Can it heal itself? Can a material be so accurately engineered that by itself it performs tasks previously requiring dozens of traditional building materials?

To address these questions, students, for the semester, become amateur biologists. Through research, they methodically isolate a biological system, and plumb its most intricate operations. Simultaneously, they weave this knowledge with their understanding of design and architecture to develop projects that perform like, not just superficially look like, biological systems. The projects are modest in scope: they may not have traditional programs, sites, or clients. However, with all the clarity of the biological systems by which they are inspired, they endeavor to question conventional architectural production.

We organize the course around two hemispheres: the architectural and the biological, or, synthesis / response and research / speculation. The semester is front-loaded with biology research to acclimate students with the complex nature of the discipline. As the term progresses they alternate between biological research and architectural design, allowing the work in one to direct the work in the next. Toward the end of studio, they spend more and more time on the design of their projects, constantly checking their work against the biological principles.

Throughout this studio, we place emphasis on unconventional thinking. We do not intend for the students to develop a comprehensive, finished, or even recognizable building. Instead, the studio serves as a venue for taking risk, working outside of one's personal comfort zone, and gaining the confidence that comes from seeing unexpected results of open inquiry.

Talley, Jennifer, Department of Biology, CWRU, Hillel J. Chiel, Department of Biology, CWRU, Edward B. White Department of Mechanical and Aerospace Engineering, CWRU, Mark A. Willis, Department of Biology, CWRU. *Using simulations to understand simple rules for odor tracking.*

Abstract: Animals use information in odor plumes to find the source of ecologically important odors. Hypotheses that propose rules by which animals alter their steering responses to odor cues are based on predictions of the sensory information thought to be available. These hypotheses have typically been tested by surgically manipulating animals to reduce the amount of sensory information available. Such methods may only reveal the strategy used by an animal with partial sensory information, not what strategy is normally employed. To address this problem we have developed simulated agents that use different tracking strategies to navigate simulated odor plumes with the goal of using the behavior of the agents to make predictions about an animal's behavior. Two disparate strategies have long been proposed for how animals use plume information to find a source of odor: 1) a spatial strategy comparing chemical concentrations of two points in space, sampled at the same time, to mediate turning behavior, and 2) a temporal strategy comparing the chemical concentrations of two points in time (as the animal moves forward) to determine a decision about whether to turn or not. We have found that the spatial strategy, but not the temporal strategy, can successfully locate the source of a simulated odor if an edge exists, where an edge is defined as the boundary between odor and clean air, or between higher and lower concentrations of odor. The advantage of the spatial strategy over the temporal strategy does not exist in an environment that does not contain such edges. These results and observations of how the simulated agents fail suggest that changing the scale of the sensor relative to the environment and including a built in turning behavior responsive to an odor threshold may provide better success at finding the source. The behavior of these strategies in different simulated odor plumes reveals what the behavior of a real animal would be if it were employing a simple spatial or temporal strategy. Predictions can then be made about the behavior of animals with manipulated sensory information.

Thomas, AnnMarie Polsenberg, John Dabiri, and Joel Burdick. *Synthetic Jets*: *Learning from Jellyfish*
California Institute of Technology

Abstract. The vast majority of underwater robots are propeller driven. While propellers are ideal for many aquatic robot applications, such as wide scale sonar surveying, there are situations where they pose challenges. Applications that involve precision maneuvering or close proximity to fragile sea life are two regimes in which alternative propulsion schemes are attractive. In the natural world propellers are rarely, if ever, the propulsion system of choice. Of particular interest to us is the jet propulsion mechanism used by many creatures. Notable examples include squid, salp, jellyfish, and nautilus. Jellyfish are particularly intriguing as they have a single orifice for inflow and outflow. They are biological synthetic jets, or zero net mass flux jets, with a net thrust. We believe that these jets could have many applications in the area of small underwater vehicles. Our work focuses on the construction and modeling of synthetic jet flow. We have constructed and studied numerous prototype jets. This talk will discuss our results and include videos of the prototypes at work. Additionally, applications and benefits of the jets will be discussed.

Turner, Scott. *Emergent homeostasis and termite mounds. A template for living structures*
SUNY-ESF

Abstract: The spectacular mound of the southern African termite *Macrotermes michaelseni* is an animal-constructed organ of physiology: a wind-driven lung for the subterranean colony. These mounds power ventilation of the nest through capturing kinetic energy in wind, and then channeling that energy through an elaborate internal network of air conduits. Most remarkably, they are also organs of homeostasis, dynamic structures that adjust their architecture according to the physiological demands made upon them. As such, these mound represent a remarkable example of a "living structure." In this talk, I will describe some of our work on how simple soil-carrying by termites is harnessed and guided to produce these sophisticated structures.

Zimmerman, Amanda[1]; Jeremy Lewi[1], Isaac Clements[1], Terrence M. Wright[2], Stephen P. DeWeerth[3], Robert J. Butera[4], *Hybrid Neural Microsystems: Bridging Neuroscience and Engineering through the development of Co-Advisory Relationships* [1]GA Tech Bioengineering, [2]Emory University Neuroscience, [3]GA Tech-Emory BMED, [4]GA Tech ECE.

A primary objective of the hybrid neural microsystems IGERT grant at Georgia Tech is to foster creative and productive scientific interactions between students and primary investigators from the biological and engineering sciences. Students are prepared to pursue doctoral thesis projects organized around the interface between engineering and neuroscience. To facilitate this process, IGERT students participate in a foundational course, Hybrid Neural Microsystems (HNM). This course uses a problem-based learning format to engage students in hybrid neural interfacing projects incorporating real-time, closed loop systems (Fig 1). The goal of this course is to introduce students to real-time closed loop methodology and build a foundation for student doctoral projects. A second aim of this course is to stimulate ideas for students as they approach their second-year projects. Second year projects involve collaborations between two investigators, one whose primary research lies in neuroscience and one whose research is more engineering focused. This year-long project will potentially serve as the foundation for their doctoral thesis as well as establish a working relationship between the two primary investigators involved. Here we present how students in the HNM course solve problems at various levels of the closed-loop methodology as well as summaries of some second year projects and how they incorporate closed-loop methodologies central to the HNM IGERT.