Keynote Paper

Development of multifunctional materials exhibiting distributed sensing and actuation inspired by fish

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ABSTRACT

This manuscript is an overview of the research that is currently being performed as part of a 2009 NSF Office of Emerging Frontiers in Research and Innnovation (EFRI) grant on BioSensing and BioActuation (BSBA). The objectives of this multi-university collaborative research are to achieve a greater understanding of the hierarchical organization and structure of the sensory, muscular, and control systems of fish, and to develop advanced biologically-inspired material systems having distributed sensing, actuation, and intelligent control. New experimental apparatus have been developed for performing experiments involving live fish and robotic devices, and new bio-inspired haircell sensors and artificial muscles are being developed using carbonaceous nanomaterials, bio-derived molecules, and composite technology. Results demonstrating flow sensing and actuation are presented.

Keywords: bio-inspired sensors, bio-inspired actuators, flexible matrix composites, lipid bilayer, haircell sensors

1. INTRODUCTION

Fish are excellent swimmers as a result of a complex muscular system that comprise more than half of the body mass. This allows them to maneuver in tight places, perform stable high acceleration maneuvers, hover efficiently, and quickly brake. Over the past twenty years, biologists have investigated a number of aspects of fish locomotor systems for movement, including studies of fish muscle structure and innervation, analyses quantifying the motor output to the locomotor musculature, and neuroanatomical investigations of spinal cord circuitry [1-3]. These studies have shown that fish possess a two-gear muscular system that controls movement, with red fibers activated for slow-speed movements, with recruitment of white fibers for rapid locomotor movements and escape responses as red fibers are turned off [4]. Fish have found innovative ways to reduce the costs of swimming and maximize net energy resources. For example, fish can swim at an optimal swimming speed that minimizes the metabolic input cost for a given output swimming speed, or fish can use a two-phase burst and coast swimming approach to minimize the amount of muscular effort over a period of time [5]. Schooling is a method by which fish use vortices from adjacent fish and fish in front to maximize swimming efficiency [6], and hitchhiking by physical attachment to a host allows fish to significantly reduce locomotor costs. Drafting is a common approach for smaller fish to be carried along by a larger fish by traveling in close proximity, and flying fish can travel a given distance using less energy than if swimming close to the surface [7, 8].

In addition to the types of energy saving maneuvers, the body shape and fin profiles play a critical role in propulsion, braking, and swimming as well maximizing the locomotor performance. Typically fin traits that increase the performance of one type of swimming behavior (e.g. steady state swimming) typically decreases the other (e.g. unsteady state). The external shape, aspect ratio, height, surface area, symmetry are all physical traits of fins. Tail fins can either be symmetric (homocercal) or asymmetric (heterocercal), and within the asymmetric shapes, tails with the lower half being larger than the upper half are called hypocercal. Epicercal tails represent tail with an entended dorsal fin. These asymmetric tails are thought to be advantageous for creating vertical forces as well as longitudinal forces (thrust) or for ushering prey. Flying fish typically have a hypocercal tail that function during take-off and continues to flap after the fish has become airborne [9]. In addition to symmetry of the tail, there is a wide variety of shapes from crescent to almost circular. Tails with a large span (i.e. height) and small surface area tend to be found on fast swimmers (e.g. sharks) whereas tails that have a large surface relative to the span provide for greater maneuverability. In addition to

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Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2011, edited by
Masayoshi Tomizuka, Chung-Bang Yun, Victor Giurgiutiu, Jerome P. Lynch, Proc. of SPIE Vol. 7981, 798103
· doi: 10.1117/12.885864

these passive traits, it is believed that fish use active control for increasing performance and efficiency. While it is difficult to differentiate passive from active control, it is believed that fish use some aspects of control such as active vorticity control, active curvature control, and active stiffness control [10]. Additionally fish can provide shape control of a fin, changing the aspect ratio and thus the hydrodynamic characteristics of the fin [11].

Despite this progress, little is known about the mechanical properties of fish tissues, the stiffness of the body as a whole and how it might be modulated during locomotion. Recent research has investigated the remarkable bilaminar structure of fish fins which have active control of curvature and hence the ability to actively resist imposed hydrodynamic loads[12], but nothing is known about the sensory control of fish body and fin position. Remarkably, fish do not appear to have muscle spindles or other mammal-like sensing structures such as golgi tendon organs within their locomotor musculature, and at this point only free nerve endings within the body connective tissue has been identified as a putative sensory receptor for locomotor muscle [13]. While it is proposed that an animal's control systems are organized as a hierarchy, there have been little or no advances obtained in describing and understanding the control architecture of fish. Biologists have explored various system identification techniques for characterizing and understanding physiological systems. Ekeberg, et al. [14] developed linear transfer models of cat hind legs in which the movements of each leg are produced by muscles whose activations follow a centrally generated pattern, however no feedback control systems were considered. Researchers have used Wiener/Volterra kernals for system identification to gain insight into the function and mechanisms underlying various biological systems. For example, orthogonalization techniques for estimating the kernel values have been developed and applied to various sensory systems, such as the catfish retina [15], the visual cortex in the cat [16], the locust and fly photoreceptor [17-19] and the cockroach tactile spine [20, 21]. Recently, researchers have used neural networks in system identification and modeling of various biological systems, such as insect walking [22], renal autoregulation in rats [23], and locomotor oscillators in lamprey spinal cords [24, 25]. However, little research has been done in understanding and identifying the hierarchical control systems found in fish.

In addition to being masters of underwater propulsion, fish have an extraordinary ability to sense minuscule changes in fluid flow through use of the lateral line. The lateral line is a mechnosensory system found in fish that can detect small water movements or pressure changes. This allows fish to detect, localize, and track prey, perform synchronized schooling maneuvers, provide feedback control for efficient locomotion, and form hydrodynamic images of the environment [26]. The smallest functional unit on the lateral line is the neuromast, which is a hair-cell receptor. The neuromasts consists of a staircase of stereocilia (up to 300 hairs) adjacent to one elonogated kinocilia, and these neuromasts are either located on the surface (superficial neuromasts) or in fluid-filled canals (canal neuromasts) [27, 28]. Surrounding the cilia is a gelatinous mass (cupula) that couples the motion of the fluid to the deflection of the hairs through viscous forces [26]. Within the neuromast, the stereocillia and kinocillia are interconnected by a number of links, which essentially act as connecting springs between ion gates located at the tips of the hairs. When deformed from fluid flow, the hairs slide relative to one another. This sliding or shearing of the hairs causes the tip links to open ion gates, which allow transduction current to enter the hair cell. This influx of cations causes depolarization of the hair cell and subsequent neurotransmitter release that is sensed by the sensory neuron located at the base of the hair cell. As a result of the staircase orientation, the hairs are more sensitive when the hairs are deflected towards the kinoilia since a greater numbers of ions flow into the hairs. It is also believed that the high sensitivity of the hair cell over a broad dynamic range is a result of the softening due to myosin-based adaptation motors attempting to position hair in region of negative stiffness [29, 30]. Hudspeth [30] measured tip deflection for an applied force on a hair bundle and found that the bundle displayed a negative stiffness within a deflection range of ±10 nm. Therefore this softening of the connecting links at the tips dominates the reaction force exerted at the base of the hairs, and thus acts as an amplifier. Despite the progress that has been achieved in understanding the lateral line sensory system, there is still little understanding in how the hydrodynamic interaction with the neuromasts affects the locomotor and muscular system or how to develop biologically inspired sensors that mimic the neuromast in form and function.

2. OBJECTIVES AND APPROACH

From reviewing the current research in fish biomechanics, control, and sensing, one can see that there is very little understanding of the structure and organization of the hierarchical control systems of fish, or in how these actuation and sensing systems are integrated to perform steady and maneuvering locomotor tasks. Additionally there is a need to transform the biological concepts related to the sensing, actuation, and control of fish into developing bio-inspired and bio-mimetic engineered materials and systems. Therefore this research aims to (a) achieve a greater understanding of the hierarchical organization and structure of the sensory, muscular, and control systems of fish, and to (b) develop advanced biologically-inspired material systems having distributed sensing, actuation, and intelligent control.

In this research we are developing a series of new biological investigations and experiments to understand how fish actively modulate the mechanical properties of the tail via muscle recruitment, how swimming gaits are influenced by the visual, vestibular, and neuromast sensory systems, and how tail and fin properties (e.g. size, shape, etc.) of various fish affect performance, efficiency, and cost of transport. To aid in understanding biology, we are developing a multifunctional material system having distributed actuation and sensing. The new material system will utilize innovative artificial neuromasts (sensors) and muscles (actuators) that are distributed and arranged as inspired by fish.

3. DISCUSSION

This manuscript is an overview of some of the research that is currently being performed as part of a 2009 NSF Office of Emerging Frontiers in Research and Innnovation (EFRI) grant on BioSensing and BioActuation (BSBA). This is a multi-university collaborative research involving faculty, post doctorate fellows, graduate students, and undergraduate students from Virginia Tech, Harvard University, and Drexel University. The co-principal investigators are Donald Leo, Harry Dorn, and Lisa McNair from Virginia Tech, George Lauder from Harvard University, and James Tangorra from Drexel University.

3.1 Understanding how fish modulate mechanical properties and how mechanical properties affect swimming

One objective of the biological portion of this research program is to identify and theoretically describe the computational processing performed at the local sensory level for muscle activation and vertebral-stiffness modulation along the tail structure of fish for locomotion. Through a series of interdisplinary engineered experiments, the research seeks to understand (a) the ability of fish to actively modulate the mechanical properties of the tail via muscle recruitment, (b) how swimming gaits are regulated by a hierarchy of control systems that involve the visual, vestibular, and neuromast sensory systems, and (c) how hydrodynamic stimuli to the lateral line neuromasts directly influence the mechanical properties of the tail.

As part of this EFRI research, the Tangorra Laboratory at Drexel University has developed a new vortex generator for 'perturbing' the fish. This perturber will be instrumental in understanding how inputs to the neuromasts along the lateral line affect the locomotor system in fish. The new vortex generator uses a compressed fluid for creating vortices that can be directed at the fish (Figure 1). This vortex generator allows us to control the strength, size, and duration of the vortex. By controlling the characteristics of the vortex, we can also minimize adverse effects due to large or unnatural impacts. When attempting to fully understand and characterize a physiological system, it is important that the fish is allowed to swim "naturally" before an analysis framework can be developed.

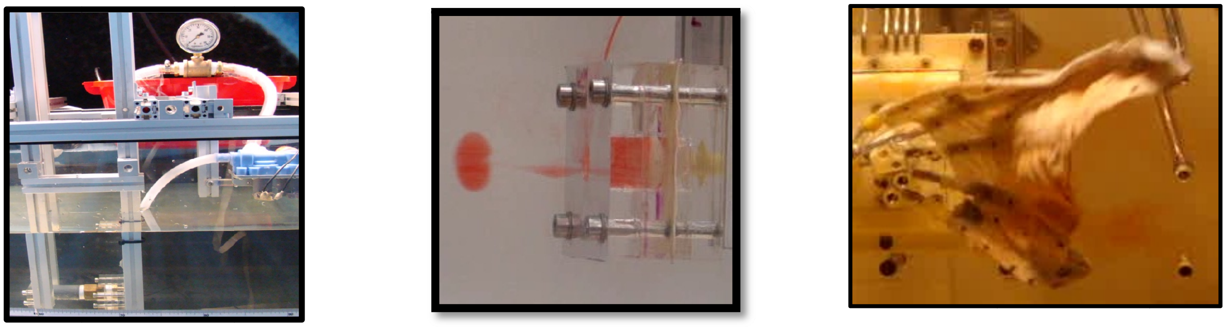

Figure 1: Vortex generator developed at Drexel University (left), an example vortex (middle), and an example vortex impacting a robotic pectoral fin.

There are many unknowns when it comes to the correlation between the fin form and body shape with respect to the swimming ability. The exchange of momentum between body and fins is not fully understood or how fish control their complex muscular system for efficient swimming in vastly limited. Therefore to increase our understanding of how fish swim, the Lauder Laboratory at Harvard University has developed a new apparatus for investigating the effects of the trailing edge shape, length, and flexibility on propulsion. The new apparatus can pitch and heave foils of various sizes and shapes while measuring the forces and moments in the x, y, z directions (Figure 2).

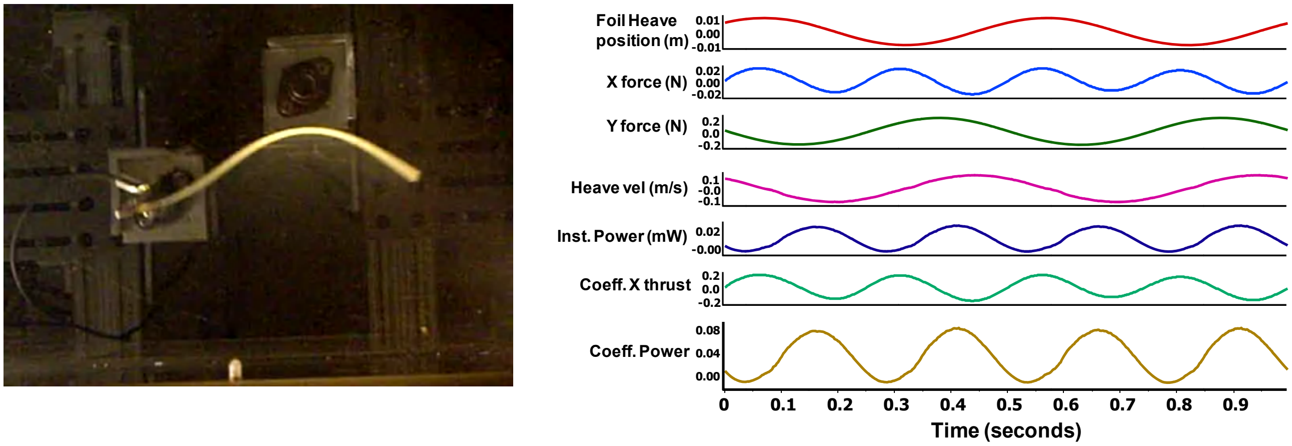

Figure 2: Image of undulating foil in water tunnel at Harvard (left) and example results from experiment (right)

There is a wide variation of fin shapes observed in biology, and the external shape, aspect ratio, height, surface area, symmetry are all physical traits of fins. Some of the work at Harvard University as part of this research program has been looking at the performance (e.g. thrust, speed, efficiency, cost of transport, etc.) of different shapes of tail fins that resemble those commonly found in nature. For example, the self-propulsion speed for five different foils heaving at a rate of 2 Hz with amplitude of 1 cm is shown in Figure 3. With the force and speed measurements, the power requirements and cost of transport can be calculated for each foil. The cost of transport is the ratio of the amount of energy expended and distance traveled, and therefore a lower cost of transport is preferred for swimming efficiency. These results show that the heterocercal tail can have a lower cost of transport than a homocercal tail under certain conditions. This research is giving important clues to why fish have certain tail shapes and important knowledge for developing more efficient bio-inspired underwater vehicles.

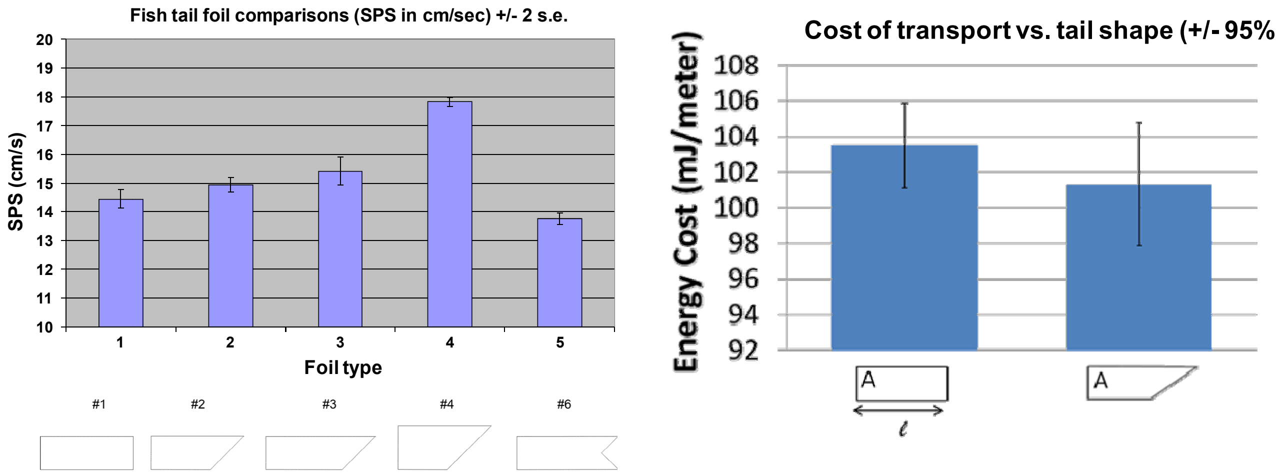

Figure 3: Self-propulsion speeds for different foil shapes (left) and an example cost of transport for two different fin shapes (right)

3.2 Development of artificial neuromasts for distributed sensing networks

Fish depend on a complex array of distributed sensing mechanisms for location, predation, and the formation of hydrodynamic images. These networks consist of soft materials that utilize ion transport as a means of transmitting information through the sensor network to the nervous system. In the past couple of decades, researchers have been developing artificial hair sensors inspired by the sensing capabilities of the hairs found in biology. For example, Liu's research group has developed several versions of artificial hair cell sensors. Early versions employed force sensitive resistors for creating a signal when the hair was deflected [31], and later versions incorporated a piezoresistive cupula using a hyrdrogel [32]. In recent years, Flatau's group has been developing hair-like sensors using magnetostrictive Galfenol and they have been able to measure a magnetic response with hair deformation [33, 34].

In this research, we are coupling new findings in fish sensory systems with recent advances in stimuli-responsive materials to produce biologically-inspired distributed sensing networks. Building upon their previous work with durable, encapsulated lipid bilayer membranes [35-37], Leo's research group has been leading the development of new biologically inspired haircell sensors that utilize lipid bilayer membranes to create a response signal (Figure 4). The lipid bilayer membranes consist of amphiphilic phospholipid molecules that self-assemble in water as spherical drops. The new haircell sensor consists of a hair embedded in a water-swollen hydrogel with a lipid monolayer fully encasing the hydrogel. Adjacent to the hydrogel is a lipid-encased aqueous volume that provides the formation of the lipid bilayer membrane. Mechanical vibration in the hair results in bending of the bilayer membrane and subsequently causes the capacitance of the bilayer to change. The changes in the capacitance provides for a measurable electrical current across the membrane as seen in Figure 4.

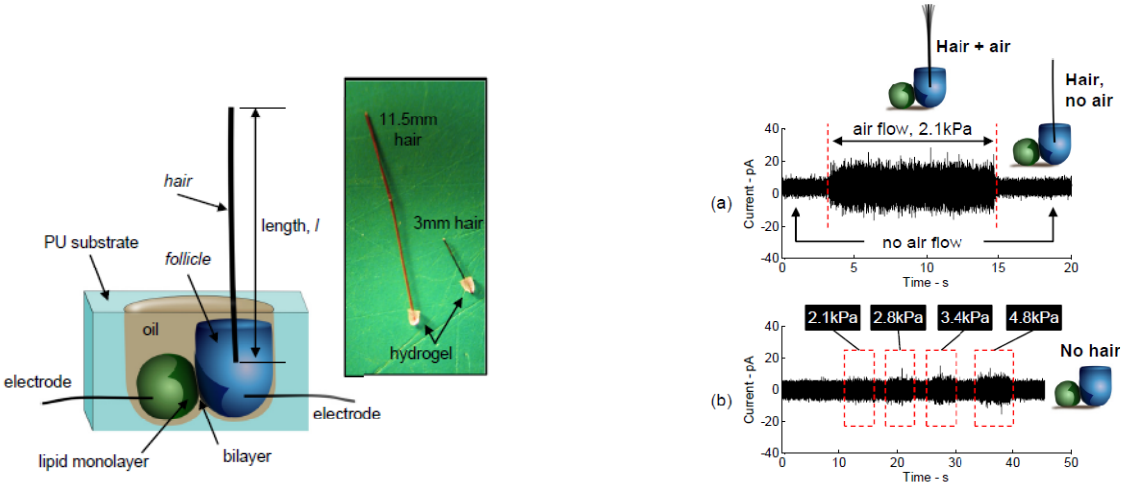

Figure 4: Artificial haircell that consists of a hair (cilium) embedded in a water-swollen hydrogel (follicle). A lipid monolayer encases the hydrogel, and an adjacent lipid-encased aqueous volume forms the lipid bilayer membrane (left). Electrical response of haircell sensor with air flowing around the hair (right)

Furthermore, in this research we are constructing artificial stereocilia by utilizing a new form of carbon, specifically single-walled carbon nanohorns (SWNHs) [38-43]. Recently, single-walled carbon nanohorn (SWNH) agglomerates have been prepared and consist of thousands of nanotubes with individual diameters of 2-5 nm arranged in structures possessing overall diameters of 50-100 nm [38-49]. Each individual SWNH has an open and a closed end; all the open ends are oriented toward the center of the structure and closed ends point out toward the periphery. Based on their morphology, they are classified by analogies to flowers into dahlia, bud, or seed types. The diameters of these pea pod structures can approach the diameter of the stereocilia found in a neuromast. SWNH are typically produced by laser ablation of pure graphite target samples; therefore, metal contamination is not an issue in the preparation in comparison with usual nanotube preparation. To date, studies of these SWNHs exhibit low toxicity [47]. The extensive surface area and multitude of interstices inherent to SWNHs permit the opportunity for addition of guest molecules. SWNH surface area can be further increased by oxidation, which causes formation of “nanowindows” in the SWNH walls to permit infiltration of a variety of molecules [*e.g.,* N_2, Ar, and fullerenes (C_{60})] into their inner space [39], thereby nearly quadrupling the adsorptive surface area.

Recently, it has been demonstrated that flow over carbon nanotubes can produce a flow-induced voltage and current [50-52]. Ghosh *et al.* showed that the induced voltage varies proportionally with the log of the liquid flow rate [52] and this effect has been attributed to a pulsating asymmetric ratcheting of the charge carries in the nanotubes where the liquid flow drags the charge carries through the nanotubes in the direction of the flow. Similarly , we have also measured a flow induced voltage and current using a PDMS substrate with carbon nanhorns attached to the top surface as shown in Figure 5. Not only does the voltage provide a means for measuring flow rate, the voltage can be used to trigger biomolecular processes of ion conduction across the lipid bilayer membrane. For example, voltage-dependent alamethicin protein channels can be gated across the membrane using a 100 mV voltage, which provides increased ion conduction across the membrane.

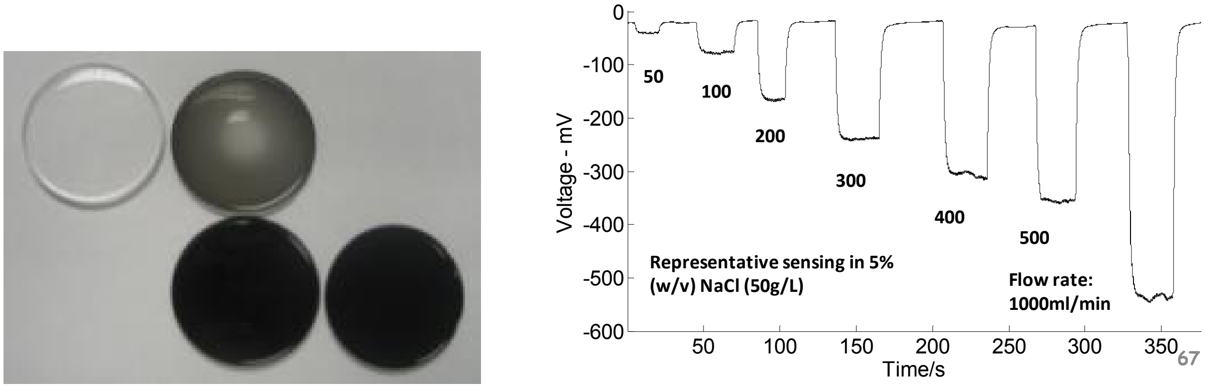

Figure 5: Several samples of carbon nanohorn (CNH) attached to PDMS substrates with different nanohorn concentrations. These samples were made in the Dorn Laboratory at Virginia Tech (left). Measured voltage vs. applied flow rate across CNH-coated PDMS device (right)

3.3 Development of artificial muscles for distributed actuation

One of the most well-known autonomous underwater vehicles is RoboTuna [53-55] developed by Barrett at MIT, which uses a system of pulleys and cable tendons actuated by DC servo motors. Other motor drive designs [56-59] and actuation methods [60-66] have been investigated for creating artificial swimming animals. Another artificial fish, developed by the Draper Laboratory [67], consisted of a rigid forward half pressure hull while the aft portion was articulated using a hydraulic actuation system. Additional robot designs, modeling challenges, and control techniques of biologically inspired soft robots have been discussed in the paper by Trivedi and Rahn [68]. Despite the accomplishments of these abovementioned works, there is still a need for an actuation system that can mimic the muscular system and achieve the swimming performance (i.e. displacement, force, response time, flexibility, efficiency, etc.) of fish.

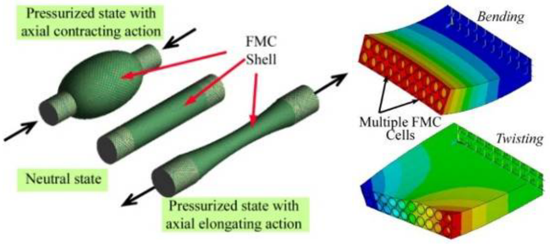

Figure 6: FMC muscles converting internal pressure to axial contraction/extension (left) and multicellular FMC adaptive skin performing bending and twisting maneuvers (right)

In this research, we are developing micro flexible matrix composite (µfmc) actuators that can be distributed in a material system. The µfmc actuators are based upon the novel FMC actuators developed by Philen *et al.* [69, 70] and Shan *et al.* [71], which are based on flexible matrix composites (Figure 6). By tailoring the fibers (orientation, number of layers, material, etc.) and selection of matrix materials, one can achieve FMC structures that have an exceptionally high degree of anisotropy

[71]. For example, the ratio of Young's moduli in the directions parallel and transverse to the fibers, E_1/E_2, can range from 10^2 to 10^4 depending on material tailoring. By designing the fiber orientation in the wall of the FMC tube, one can cause the actuator structure to contract or elongate due to internal pressurization. In Philen *et al.*[69] FMC actuators were able to achieve more than 20% axial free strain and a block stress 20 times greater than the input pressure in the laboratory. These interesting actuation properties can be carried over to form adaptive skins with multi-directional actuations by integrating multiple FMC cells (tubes) into a continuous structural system as illustrated in Figure 6. When the FMC composite tubes are combined with an internal fluid having a high bulk modulus (e.g. water, oil), one can obtain significant changes in stiffness through simple valve control [72]. In fact, a stiffness change greater than 10^3 can potentially be achieved with the technology [72] and a stiffness change greater than 52 has been measured in the laboratory [73]. While simple on/off valve control can provide the adaptive material with two modes of operation, i.e. soft or stiff, active valve control can significantly enhance the variability of the impedance of the adaptive materials. The ability to 'tune' the impedance to a desirable value has considerable advantages over simple on/off valve control such as greater variability of impedance and increased performance ideal for modulating the tail structure. In Philen [74], impedance tuning of a fmc structure was demonstrated both analytically and experimentally.

As a result of the abovementioned properties, the μfmc composite actuator can provide distributed actuation as well as precision stiffness modulation when the working fluid is water. These characteristics are ideal for developing a biologically inspired autonomous vehicle since the muscular system of fish possesses similar capabilities. It is believed that fish possess the ability to actively modulate the kinematics and the stiffness of the body and fins [75, 76] and continuously tune their movements as well as mechanical properties to create and control vortices along the body. This feedback control of the dynamic interaction with the fluid through fin and muscular modulation provide for efficient swimming and high maneuverability.

In recent months, we have achieved significant reductions in the diameter of the fmc actuators using a closed-mold casting process. Shown in Figure 7 are examples of fmc actuators with a diameter of 2 mm. Also shown are pictures of the actuator when pressurized, showing an actuation strain greater than 16%. In addition to manufacturing the fmc actuators with a smaller diameter, we have also developed new analysis tools that can capture the inter fiber compaction as well as geometric and material nonlinearities of the fiber during actuation. It is observed that the inter fiber compaction can reduce the effective stiffness of the water-filled fmc actuator when the valve is closed as shown in the right plot of Figure 7.

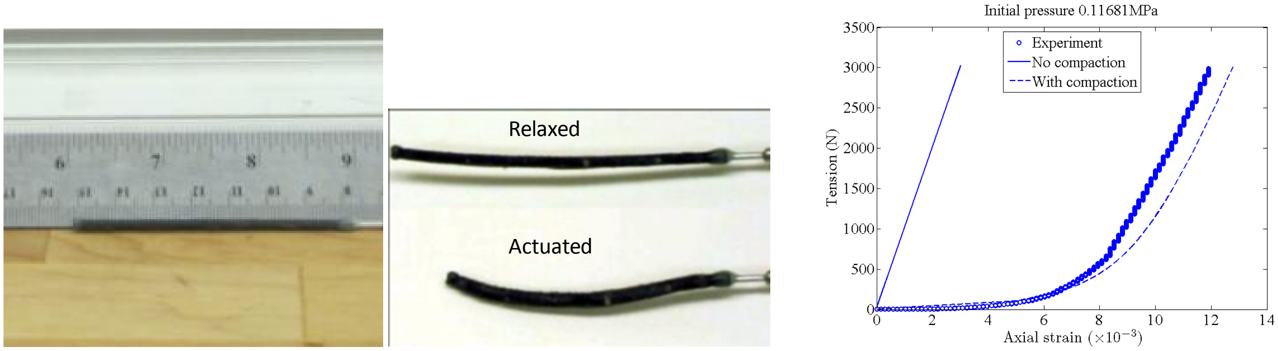

Figure 7: Image of fmc actuator with diameter of 2 mm in a relaxed state and actuated (left). Analysis and experimental results for new model that captures inter fiber compaction as well as geometric and material nonlinearities. (right)

4. CONCLUSIONS

Presented are some of the results from a new interdisciplinary research program funded by the NSF Office of Emerging Frontiers in Research and Innnovation (EFRI) on BioSensing and BioActuation (BSBA). This research is providing greater insight into the systems that fish utilize for sensing, actuation, and tail stiffness modulation. New experimental apparatus have been developed for performing experiments involving live fish and robotic devices. Recent results are illustrating the importance of the fin shape and geometry in fish propulsion, and new bioinspired haircell sensors and actuators are being developed. The biological experiments for the fish and engineering experiments using the synthetic material will guide and couple to one another for understanding how the actuation and sensing systems are integrated to perform steady and maneuvering locomotor tasks as well as tail stiffness modulation. Furthermore, the collaborative nature of this research is providing the students with interdisciplinary training and a unique research experience. The students are realizing the need and synergistic importance for bringing different disciplines together in understanding many engineering and physiological systems.

ACKNOWLEDGEMENTS

The author gratefully acknowledges financial support from the National Science Foundation Grant EFRI-0938043. I would like to thank my team members Drs. Harry Dorn, George Lauder, Don Leo, Lisa McNair, and James Tangorra as well as all of the graduate and undergraduate students working on this project.

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