Applications of conducting polymers: robotic fins and other devices

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ABSTRACT

Conducting polymers are becoming viable engineering materials and are gradually being integrated into a wide range of devices. Parallel efforts conducted to characterize their electromechanical behavior, understand the factors that affect actuation performance, mechanically process films, and address the engineering obstacles that must be overcome to generate the forces and displacements required in real-world applications have made it possible to begin using conducting polymers in devices that cannot be made optimal using traditional actuators and materials. The use of conducting polymers has allowed us to take better advantage of biological architectures for robotic applications and has enabled us to pursue the development of novel sensors, motors, and medical diagnostic technologies. This paper uses the application of conducting polymer actuators to a biorobotic fin for unmanned undersea vehicles (UUVs) as a vehicle for discussing the efforts in our laboratory to develop conducting polymers into a suite of useful actuators and engineering components.

1. INTRODUCTION

Conducting polymers are a class of high molecular weight engineering materials with vast degrees of freedom in their molecular composition and which enable the construction of system-level engineering devices. This class of materials was chosen for research in our laboratory based not only on their key contractile features, such as low drive voltages and high strength,[5, 10] but also because of their potential to be used to build components and complete systems. To date, actuators, low level sensors (force, displacement, chemical, and optical), transistors, electrical elements (wires, diodes) and energy storage devices (capacitors) have all been demonstrated using conducting polymers.[12] This implies that full systems can be constructed using conducting polymers that are able to manipulate both energy and information. In a manner similar to that used by Nature to grow systems from a small set of building blocks, it can be envisioned that complex systems will ultimately be grown, or co-fabricated, electro-chemically from conducting polymer constituents. [11]

We have taken a multi-level approach to the development and improvement of conducting polymer technologies; from the design of materials with specific molecular level properties, [19, 1] to mechanical and electro-chemical processing to improve the behavior of polymers films,[13] to the development of component level devices (see Fofonoff and Hunter in these Proceedings). This multilevel approach has led us to move beyond the synthesis and characterization of actuator sand to see these materials as an enabling technology for system-level solutions. In the case of actuator development, for example, what is desired is an integrated actuator that can produce and control a specified force, displacement, and speed - in other words, a system level force-motion device. Such a solution will require a position sensor, control and switching electronics, wires to transfer information (control) and energy, and energy storage device. The appeal of conducting polymers is that all of these components can potentially be co-fabricated, or electro chemically grown, from the same class of materials.

This paper uses the application of conducting polymer actuators to a biorobotic propulsor for unmanned undersea vehicles (UUVs) as a vehicle for discussing the efforts in our laboratory to develop conducting polymers into a suite of useful actuators and engineering components. In particular for the robotic fin, parallel actuated conducting polymer films were used as artificial muscles to power the swimming movements and control the stiffness of a flexible robotic fin, bending trilayers were used to control the fin's shape and surface conformations, and the development of all polymer servo-mechanisms for the control of both the linear and bending actuators was begun.

2. BIOROBOTIC PECTORAL FINS

Many commonplace fish, such as the sunfish and the perch, are capable of performing maneuvers such as hovers, yaw turns, and rolls that are difficult for man-made underwater vehicles to perform well. The ability to maneuver like this is due largely to the fish's paired pectoral fins, which can produce and control forces in three dimensions.[3, 8] The pectoral fins are also able to produce positive thrust throughout the fin beat; during both the fin's outstroke (abduction), instroke

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(adduction), and even during the transition from the out- to the instroke. Because of these performance characteristics, the pectoral fin of the bluegill sunfish (*Lepomis macrochirus*) was selected as a biological model from which to create a propulsive device that gives AUVs higher levels of maneuverability.

Fundamental principles that related fin movements, flexibility, and the active control of shape and stiffness to the production and control of thrust were identified from studies of the kinematics, hydrodynamics, and anatomy of the sunfish pectoral fin. These principles were used to identify important functions and behaviors that were desirable for robotic fins to have or to be able to perform.

First, the movement of the sunfish pectoral fin is complex, but it can be reduced into a small set of motions that can be more easily understood and studied. Proper orthogonal decomposition (POD)[2] was used to decompose the motion of the pectoral fin into four component movements that together, accounted for the production of over 90% of the fin's thrust. These component motions were: 1) a sweep of the fin forward and back; 2) a cupping of the fin about its spanwise axis as the fin is swept forward, and the un-cupping of the fin during the in-stroke; 3) an expansion of the fin's area during the in-stroke; and 4) a high frequency "flick" of the fin's dorsal, distal tip.[16]

Secondly, the flexibility of the fin is crucial to the production of thrust, particularly during the fin's out-stroke. The "tip-flick" is the result of the dynamic interaction between the flexible fin and the fluid, and was shown via CFD to increase thrust by nearly 50%, as compared to when it was omitted. It was shown experimentally using robotic fins that a movement resembling the tip-flick was created only when the flexibility of the fin was appropriate for the frequency at which the fin was swept, and that the biorobotic fins produced positive thrust during the out-stroke only when the fin flexibility was tuned properly.

Thirdly, the fin rays of the biological fin provide a means for the fish to control the fin's shape, and to modulate its stiffness, without compromising the thinness and flexibility of the fin. Each of the biological fin rays has two halves and the curvature and stiffness of the fin ray is controlled by displacing the position of its bases relative to one another. This method can be used in the robotic fin to alter the overall shape of the fin, to modulate the fin's stiffness during a fin beat which affects the magnitude of the forces produced, and to actively tune the flexibility of the fin as operating conditions for the fish change.

2. 1 Robotic fins

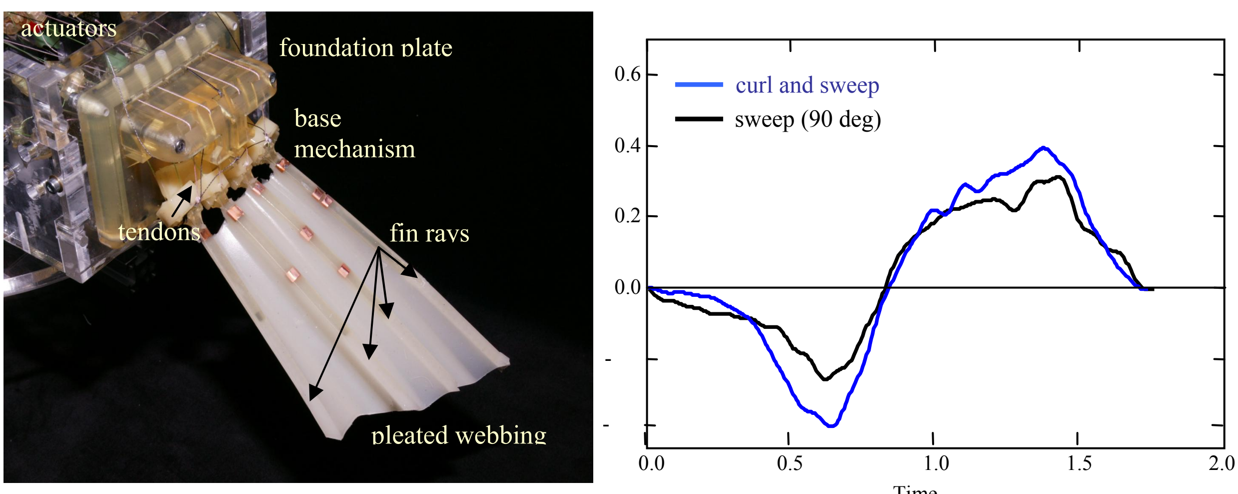

Figure 1: Robotic fin and the thrust created when swept through water.

Two versions of robotic fins were built using traditional engineering materials and actuators, and were used to investigate the effects the above characteristics had on hydrodynamic forces. The first fin design was based heavily on the architecture of the sunfish (Figure 1), and its main objectives were to have the degrees of freedom, level of control, and appropriate dynamic interaction with the water to approximate the four fundamental movements of the sunfish fin. The basic design used five fin rays embedded in flexible urethane webbing. The webbing was pleated so that it could be expanded easily, and the fin rays had two halves so that their curvature and stiffness could be controlled actively. The bases of the fin rays were attached to a compliant base mechanism that served a similar same purpose as the radial bones and cartilage pad in the sunfish – it supported the fin rays, but was flexible and allowed the base of the fin to move and be reoriented. The compliant base was mounted to a rigid foundation plate which connected to an array of servomotors that controlled the fin rays via nylon tendons.

These fins were able to produce motions that approximated closely the four fundamental movements of the fish pectoral fins, and these motions could be combined to create more complicated fin movements (Figure 2). The sweep, curl, and expansion components affected the production of force in a manner that was expected: force could be modulated by the fin's curl, which affected the fin's stiffness, and by expansion, which affected the fin's area. When added to other motions, cupping reduced the magnitude of the drag force, but did not cause the biorobotic fin to produce thrust during the out-stroke as is done by the sunfish. This was possibly due to the drag from the other components being significantly greater than the thrust produced by the cupping motion. The results did show, however, that when cupping was activated alone, two positive thrust peaks were generated.

Figure 2: Component motions: from left to right, fih relaxed, expanded, curled, and cupped.

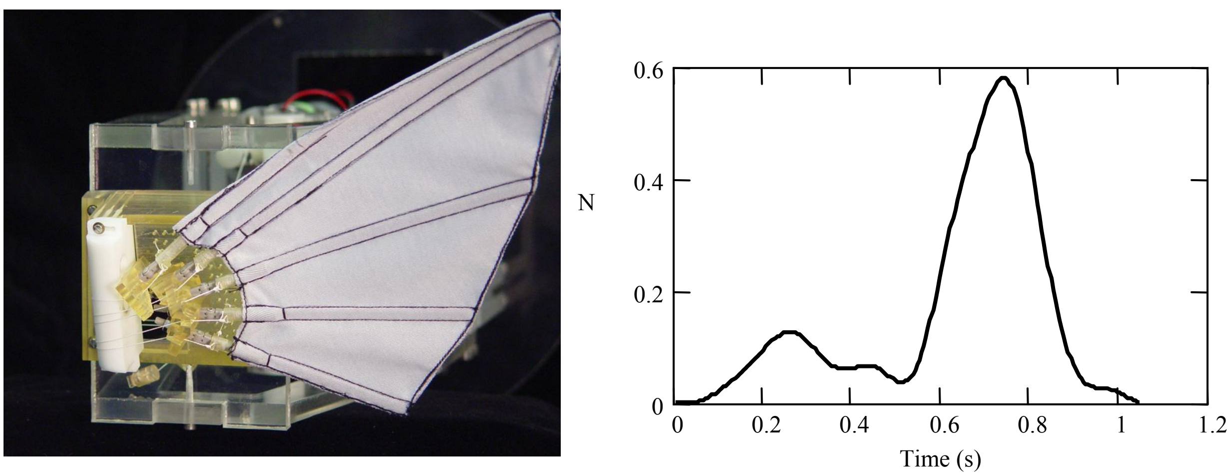

Figure 3: Fin and thrust plot. Positive thrust was created during both the outstroke and the instroke.

The second series of fins had a simpler design, and were developed to recreate the cupping and sweep motion of the pectoral fin and to investigate the effect of fin flexibility on force production (Figure 3). In this design, the fin rays were attached to small diameter hinges mounted into a curved, rigid base. The curvature of the base caused the rays to move along paths that made the fin cup as the rays were swept forward. The fin rays and the fin webbing were flexible, which allowed for a dynamic interaction between the fin and the water to exist, but the fin ray bases were constrained to rotate within the planes defined by the location of the hinge rotation points, the curvature of the base, and the angle the hinges were placed within the base.

Like the sunfish, these fins produced positive thrust during both the fin's outstroke and instroke (Figure 3). The magnitude of the force was dependent on the flapping frequency and flow velocity, but in general, two thrust peaks were produced; a small one as the fin cupped forward, and a larger peak as the fin uncupped and was swept back. The data from test trials conducted with fins of different stiffness at numerous flapping speeds and flow rates suggest that to maximize thrust, fin flexibility must be tuned to flapping frequency and flow rate.

2.2 Desire for conducting polymers

The robotic fins were able to create movements and forces like the fish fin, but it became apparent during their construction that the size, rigidity, and weight of traditional servomotors limited the degree to which these fin designs could be miniaturized and incorporated into small AUVs without losing important functional aspects of their biologically based design. Conducting polymers were therefore envisioned for use as a technology that could be used in lieu of traditional motors to create flexible fins that could be housed inside a small, flexible bodied AUV. The forces (1-5 N), displacements (10-15 mm), and speeds (0.4-1.0 Hz) required to actuate the fin rays were not unreasonable for conducting polymer actuators, but it was recognized that further development of conducting polymer actuators was required in order to produce these values simultaneously. However, conducting polymers could immediately bring functionality to the fins that could not be achieved using traditional actuators, by being introduced directly into the fin webbing and increasing the level of active control had over the fin's shape.

3. APPLICATION OF BENDING AND LINEAR CONDUCTING POLYMER ACTUATORS TO THE FIN

We envisioned that in an operational AUV, conducting polymer actuators would be used to control the cupping, stiffness, and surface conformations of the fin and that a small number of traditional actuators would be used to drive the fin's basic sweep motion. Trilayer bending actuators, which, due to their construction, produce small forces, but large strains (curvatures), would be used in, and as, the fin webbing. This would provide a means to actively control the fin's entire surface, rather than just the bases of the fin rays as are actuated in the biological fin. Linear actuators, which can produce large stresses, but moderate displacements and slow contraction speeds, would be used to modulate the fin ray's curvature and stiffness by controlling the fin ray bases. In terms of the functional objectives, the specific goals set for polymer actuated fins were to control the cupping of the fin's dorsal and ventral edges with bending actuators, and to control the curvature of the fin rays using linear actuators. In both forms, we want the actuators to be servo-positioned, just as is desired when using traditional actuators.

3. 1 Trilayer bending actuators

Three approaches were taken in our effort to use trilayer bending films to create fins that had several areas of the web under active control and that were able to produce the cupping motion of the sunfish pectoral fin.

The first polymer actuated fin was constructed by sandwiching two bands of bending actuator within two thin (100 μm) polyester films (3M Visual Systems, Austin TX) (Figure 4). The films and the polymer actuators were cut into the shape of a sunfish pectoral fin, with the polymer actuators located along the fin's base and across its distal end. Long slits were cut into the fin from the base to its distal end. The polyester films acted as the fin's web and provided structural support for the polymer actuators, and the spanwise slits served to separate the fin into 5 sections and to reduce the stiffness of the fin so that it could be more easily cupped. Copper tape was laid out in a branch pattern to provide electrical contact to the conducting polymer actuators in each of the five lateral sections, and conductive adhesive was used to ensure contact.

This fin was able to produce a moderate cupping motion, but the speed of actuation was slow and most of the curvature occurred towards the lateral edges. Approximately 10 s was required to complete the motion. The five sections of the fin could not be controlled independently because the polymer films were continuous across the slits and therefore each section was not isolated electrically. However, by applying voltage selectively to the electrodes the local curvature could be influenced and the speed of actuation increased. The shaping of the polyester film and the spanwise slits constrained the fin to move in a pure cupping motion, as opposed to curling along a non desired direction, but we suspect that the stiffness of this film was too great, and the angles of the slits not aligned properly, for the trilayer to exhibit a larger cupping motion.

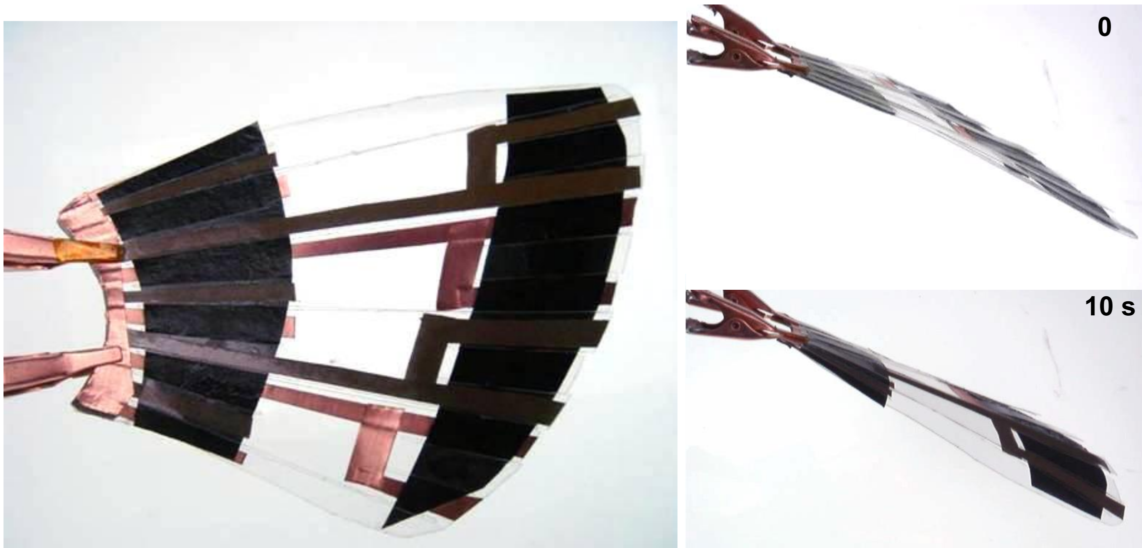

Figure 4. Fin constructed using trilayer bending actuators sandwiched between two layers of polyester film. The cupping motion was actuated using a ± 4.5 V at 0.05 Hz square wave.

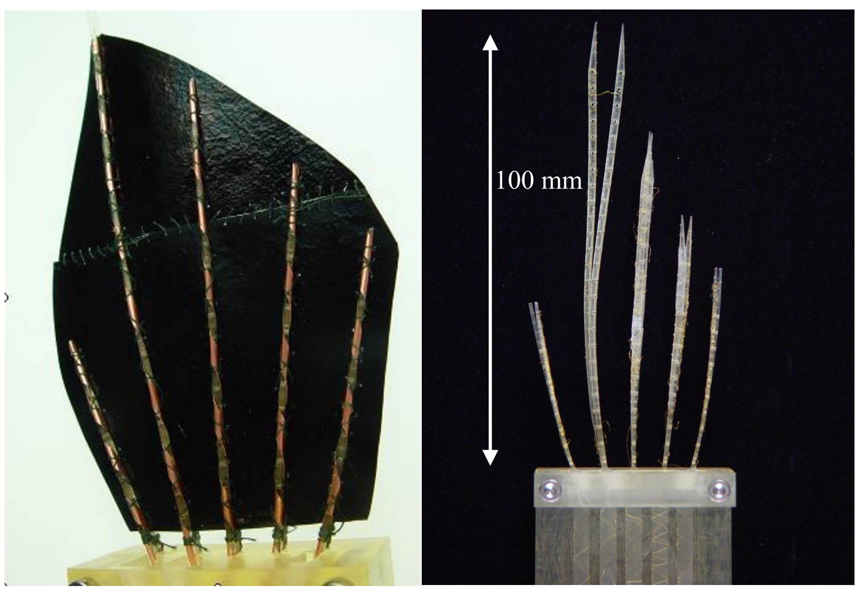

Figure 5. The second polymer-fin prototype used flexible urethane members (right) that simulated the fin rays of the pectoral fin and served as a means to constrain the polymer film to the desired cupping motion.

In the second prototype, a conducing polymer film was used as the entire fin webbing, rather than being treated as an actuator that needed to be housed within a separate web. A large trilayer film was placed into five flexible "fin rays" (Figure 5) that constrained the fin to move with the desired cupping motion. Each fin ray was attached to a very low stiffness flexure which allowed the fin rays to move along a curved path in the direction perpendicular to the surface of the trilayer film. Copper and gold tape was wrapped around each fin ray in order to provide electrical contact to each side of the trilayer film, and the large trilayer film was sewn onto the rays via a needle and thread. By providing electrical contact along the lengths of fin rays, rather than localizing the electrodes at the fin's base, we believed that we would be able to increase the speed and strength of the cupping motions by driving the ions of the electrolytic gel simultaneously throughout the fin.

Although the trilayer films moved visually when voltage was applied, the fin failed to move with the desired cupping motion. We do not believe that this was due primarily to the stiffness of the fin rays or the flexure being too great, but speculate that it may have been due to failing to recognizing that large films have a predisposition to bend about particular axes, and not aligning these axes with the direction of motion constrained by each of the fin rays. The bending of a trilayer actuator is often explained as occurring like a bilaminar strip, with one side of the trilayer expanding and the other contracting. With few exceptions,[7] experiments with trilayer actuators tend to constrain films at only one end and/or use a long film that curls most naturally about its shorter width. In contrast to this, the trilayer films that were used to make the fin webs were rather square and large (100 mm x 100 mm), and had multiple electrodes running through the fin that prevented motions except in a predefined direction. In experiments with our third fin design, we were able to produce the cupping motion nicely by identifying the axis along which the large film naturally bent and using physical constraint to enhance the motion.

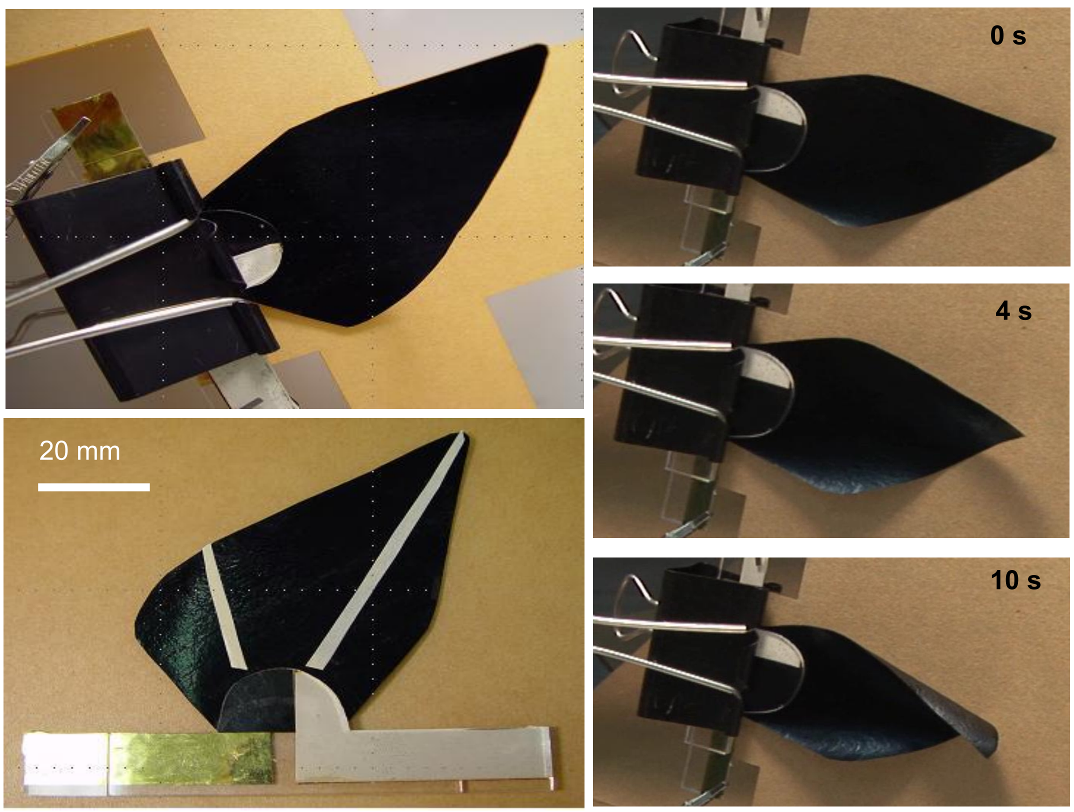

Figure 6: An all polymer fin with light ribs affixed to the back to increase fin stiffness in the spanwise direction. This fin was able to cup the dorsal and ventral edges, and to create a sweep motion.

The third and most successful of the fin designs used a trilayer film as the fin's webbing, like for the second prototype fin, but had few physical constraints placed on the film's motion. The fin was made by cutting a trilayer polymer actuator into the shape of a pectoral fin and affixing two light Mylar ribs onto the back of the fin. The ribs were flexible, but made the fin stiffer along the span from the base to the distal end, and encouraged the upper and lower edges of the trilayer to fold over and create the cupped shape (Figure 6). Electrical contact was made with the polymer films by clamping the fin's base between two layers of gold backed Mylar film. The curved base helped create the cupped shape by restricting the motion of the fin more along the midline than on either edge. The trilayer actuator film was cut, and the ribs affixed to its surface, only after the film had been actuated, and the directions the film preferred to bend were known.

This pectoral fin exhibited a large cupping motion. The upper edge was able to bend through more than 90 deg, and the lower edge achieved about 45 deg, which is comparable to motions made by the biological fin. The motions, however, were slow. A full 10 seconds was required to reach the fully cupped stage. In addition to the cupping motion, this fin could be made to sweep forward and back at its base by changing, slightly, the placement and activation of the electrode. The sweep motion was much faster than the cupping, requiring less than 2.5 sec to bend 90 deg.

The results of these three prototypes show that conducting polymers trilayer actuators can be used to create surfaces with varying 3D geometry. In particular these polymer devices can replicate, in part, the cupping and sweep motion of the pectoral fin. Mechanical constraints and structural elements printed using a 3D stereolithography printer or cut out of lightweight plastic transparency film allow control of the direction of the polymer bending. While large cupping deformations can be achieved and held by these polymer devices, speed remains limited with these large devices. For example, our fasted fin, shown in Figure 6 exhibited a full contraction in about 10 s, whereas a contraction in 1-2 seconds is likely required to recreate the hydrodynamic effects used by the sunfish fin to produce force. The incorporation of electrically conductive structural elements in the polymer trilayer would allow the delivery of charge faster within the whole area of the polymer fin, thus increasing the speed of the devices.

3. 2 Linear Actuators

Linear conducting polymer actuators are being developed to control the curvature and stiffness of the robotic fins. The linear actuators will be integrated along the skeleton of the fin rays, and like an agonist-antagonist muscle pair, will pull on opposing bases of a fin ray.

Given the active stress and strain capabilities of polypyrrole films, the forces, displacements, and strain rates that are required to actuate the robotic fin rays can be met, at least in principle, by an appropriately designed linear polymer actuator. The robotic fins that are being developed have linear dimensions that are approximately 4 times that of the biological fin, and to maintain similarity with the biological fin are flapped between 0.4 Hz and 0.8 Hz. We have calculated that the curvature of a robotic fin can be controlled satisfactorily for use in maneuvering motions by producing a force of 1-5 N over a displacement of 1-2 mm, at rates of 3.0-10.0 Hz. In general, a contractile material that is capable of generating a certain stress, strain, and strain rate, should able to achieve a specified force, displacement, and cycle time by appropriately selecting the material’s cross section area, length, and distribution. There are limits to this approach when using conducting polymers, however, as several difficulties arise when the polymer films are scaled to larger sizes. These difficulties include the uniformity and sheer size of the synthesized material, a reduction in speed in lengthy and thick actuator films, actuator lifetime, actuator encapsulation, and the overall mass and size of an actuator system that includes the polymer film and support systems. Although linear polymer actuators have not to date been incorporated into a full scale biorobotic fin, significant progress has been made in producing actuators that generate the required displacements and forces, and that have improved speeds of actuation.

Our efforts to make linear actuators that are appropriate for the fin have progressed along two main fronts. The first is the fabrication of long, uniform polymer ribbons with gold backing. The long ribbons, which can be of lengths greater than 10 m, can contract over displacements that exceed the requirements of the fin. The uniformity of the film enhances its actuation qualities, and the ability to characterize and control their performance. The gold backing increases the speed of actuation by serving as an electrical bypass along the length of the polymer, thus reducing the distance through polymer that charge must pass during actuation. This increases actuation speed by reducing the ohmic potential drop from the working electrode along the polymer.

The second effort is in the creation of parallel actuation devices that can produce forces on the order of several Newtons while retaining appropriate actuation speeds. Rather than increasing the force of a single polymer film by increasing its cross section area, the strategy mimics that of skeletal muscle by actuating many thin films in parallel. The latest device, which is shown is figure 7, can produce 2-4 N.

Details on the gold backed, polymer ribbons and the parallel actuation devices can be found in the article by Fofonoff and Hunter in this issue of the Proceedings.

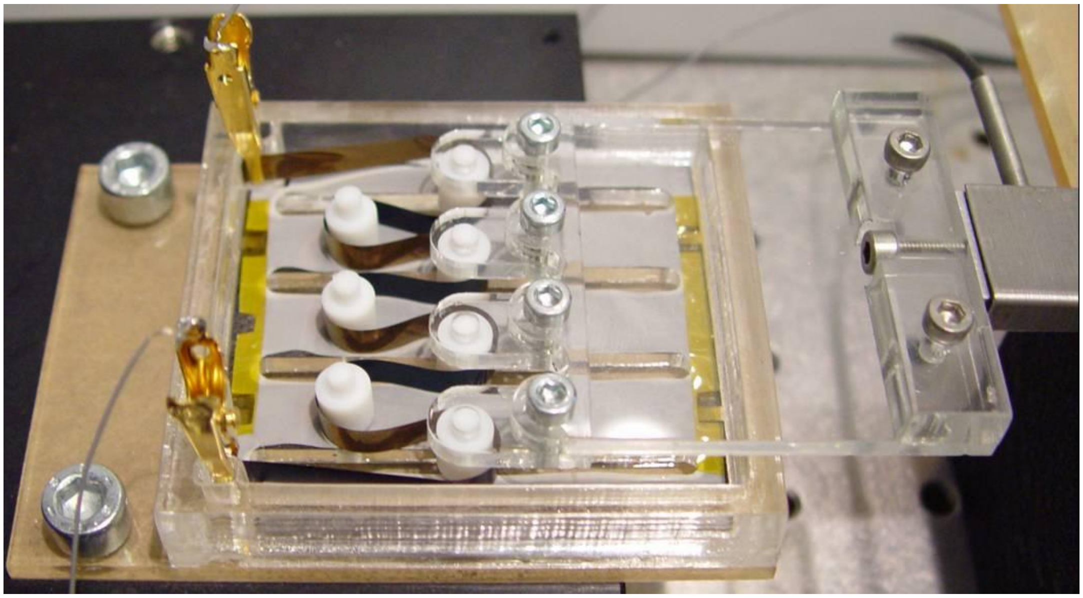

Figure 7: Parallel actuation device. A single gold backed film is snaked around Teflon bearings to create the equivalent of 8 films acting in parallel. This device generated forces in excess of 2N.

3.3 Servo positioning

Having a flexible actuator that can produce the required levels of force, displacement, and speed is necessary, but is not sufficient for applications such as the fish. In order to make the polypyrrole actuators as useable as traditional actuators, we are developing from polypyrrole the necessary components and circuitry to transform the simple actuators into servomotors. Feedback control of polymer actuators has been done previously using fabric-based strain gauges and computerized control components,[6,15] but in line with our desire to "co-fabricate" all-polymer devices, a position controlled device is being constructed using polypyrrole as the actuator, the position sensor, and as a differential amplifier.

Polypyrrole position sensors have been created by placing polymer films in mechanical opposition to the linear actuator. The film's resistance changes as a function of strain, and a constant current input will produce a variable voltage output which can be used as a position feedback signal for control of the actuator. Tests conducted with polypyrrole films deposited in propylene carbonate with hexafluorophosphate dopant ions have produced good initial results, but stress relaxation of the film is a problem that must still be overcome. Further testing with films from other deposition conditions, as well as stretch-aligned films, is being done to improve both the reliability and sensitivity of the sensors.

To create a feedback signal that can drive the position of the actuator, the signal from the position sensor must be compared to an external signal that represents the desired position. This comparison requires the construction of a differential amplifier. The components (resistors, capacitor, and transitors) required to produce a differential amplifier can all be made by properly patterning and layering polypyrrole. Various methods are available for appropriately patterning polypyrrole for control electronics,[14, 17] and one of the most promising is the oxidative chemical vapor deposition (oCVD) process devised by Lock, et. al..[18] This method was developed originally for deposits of poly(3,4-ethylenedioxythiophene), but was converted to deposit polypyrrole since the oxidation species used ($FeCl_3$) has been successfully used to deposit polypyrrole on fabric.[4] Using the oCVD process, initial results have demonstrated the viability of creating RLC (resistor, inductor, capacitor) elements using layers of two-dimensional patterns of PPy. Patterning transistors has been accomplished,[9, 11] and including them in this work is envisioned using the techniques of Chen. [17]

Integrating the individual components of a polymer servo-actuator (actuation, sensing, control electronics) remains a challenge, but in doing so we will have created a fully integrated, position controlled actuation device that can be co fabricated from a single polymer.

4. CONCLUSIONS

We are still in the early days of co-fabricating entire systems from the same class of polymer, but the potential for doing so is great and has motivated us to shift our focus from producing film actuators to developing conducting polymers based systems. Although conducting polymers are not yet mature technologies that can be used in designs easily, great progress is being made in solving the engineering challenges that must be overcome for conducting polymer systems to be considered viable engineering devices and to become widely used.

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