ELECTROACTIVE POLYMER ARTIFICIAL MUSCLE FOR UNDERWATER ROBOTICS

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Abstract

Electroactive polymer artificial muscles (EPAM) made from dielectric elastomers have been demonstrated in many applications. As an electrical generator, EPAM has produced 0.8 W of power within the heel of a boot. As an actuator, EPAM has propelled several terrestrial biologically inspired robots at speeds up to 14 cm/s. EPAM has also been demonstrated effectively as a pump, speaker, and sensor. This paper discusses the potential for the use of EPAM in underwater robotics, primarily in the areas of propulsion, maneuvering, and power generation.

EPAM Background

New actuator materials are needed for a wide range of demanding applications, such as robotics, micro air vehicles, disk drives, flat-panel loudspeakers, and prosthetic devices. Many types of candidate materials are under investigation, including single-crystal piezoelectric ceramics [Park, 1997] and carbon nanotubes [Baughman, 1999]. Electroactive polymers are of particular interest because of the low cost of the materials and the ability of polymers to be tailored to particular applications. Within the general category of electroactive polymers, many different types are under investigation, including electrostrictive polymers, piezoelectric polymers, and electrochemically actuated conducting polymers and gels. Most electroactive polymers excel in some measures of performance (such as energy density or strain), but are unsatisfactory in others (such as efficiency and speed of response).

It has been well known for many years that the electric field pressure from free charges on the surface of all insulating materials induces stresses (Maxwell's stress) that strain the material. Zhenyi et al. [1994] showed that a largely noncrystalline polymer (polyurethane) could produce actuated strains of 3 to 4% using metal electrodes such as 20 nm thick gold; they estimated that 10% of their observed strain response was due to Maxwell stress. More recently, it has been suggested that Maxwell stress by itself can produce powerful electroactive responses in certain elastomers [Kornbluh et al., 1999 and Pelrine et al., 1998]. This mechanism of actuation, shown in Figure 1, distinguishes dielectric elastomers from electrostrictive polymers previously reported. A dielectric elastomer film, typically 10 to 200 µm thick, is coated on each side with a compliant electrode material (e.g., carbon-impregnated grease). When a voltage is applied across the two electrodes, the electrostatic forces compress and stretch the film. Compression of the film thickness brings opposite charges closer together, whereas planar stretching of the film spreads out or separates similar charges. Both thickness compression and planar stretching convert electrical energy to mechanical energy and provide the actuation mechanism.

Strains as high as 380% have been measured, with actuation pressures up to 8 MPa. The available literature indicates that the actuated strains of dielectric elastomers like silicone are greater than for any known high-speed electrically actuated material (that is, a bandwidth above 100 Hz). Silicone elastomers also have other desirable material properties such as good actuation pressures and high theoretical efficiencies (80 to 90%) because of the elastomers' low viscoelastic losses and low electrical leakage.

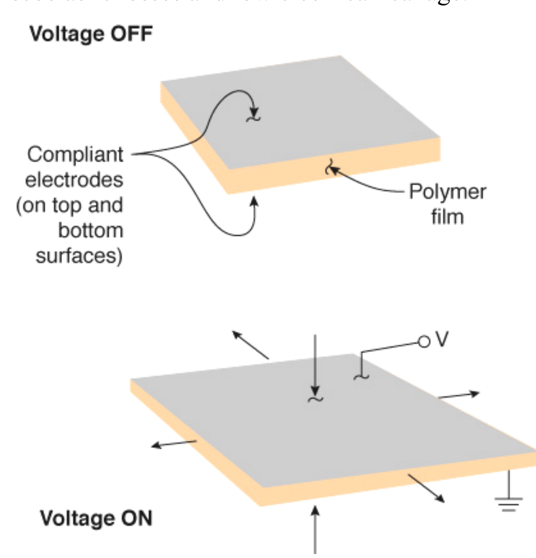

Figure 1. Principle of actuation.

The energy density of dielectric elastomer EPAM has reached 3.4 J/g, about 21 times that of single-crystal piezoelectrics and more than two orders of magnitude greater than that of most commercial actuator materials [Pelrine et al., 2000].

EPAM Devices

There are numerous ways to extract useful work out of the 2-D expansion of the dielectric film. A diaphragm is a very simple mechanism made by constraining the edges of the electroded area of film. When the film is actuated, it is unable to expand within the plane, so a small mechanical bias (e.g., by foam or air pressure) causes the film to bulge or "balloon" out of the plane. This has been used to create pumps (Figure 2), compressors, and even high fidelity speakers (Figure 3).

Another method of actuation is to create a bimorph or unimorph by attaching the film to a nonelastic but flexible surface. A flow control device made from an EPAM unimorph is shown in Figure 4.

Perhaps the most effective actuator to date for many applications is the spring roll. In this design (shown in Figures 5 and 6), the film is wrapped around a compressed spring, which is subsequently released. The freestanding roll then holds the film in tension, which augments the performance and constrains the motion axially. By rolling the film, multiple layers stack upon one another, increasing the available force. From an applications point of view, this 1-DOF spring roll is equivalent to a pneumatic actuator or solenoid. Note, however, that the EPAM spring rolls can be controlled linearly, unlike their counterparts which are often limited to highly nonlinear, "on-off" type response.

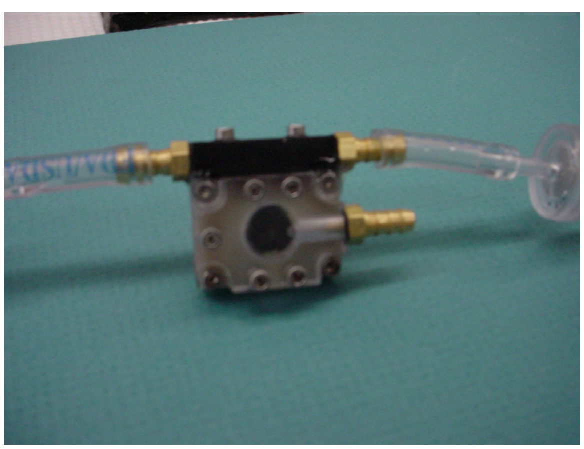

Figure 2. A low frequency EPAM diaphragm pump.

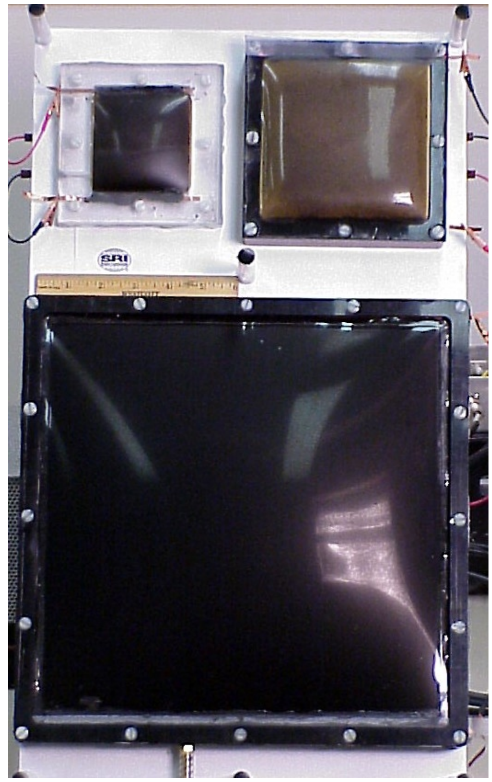

Figure 3. High frequency EPAM diaphragm speakers.

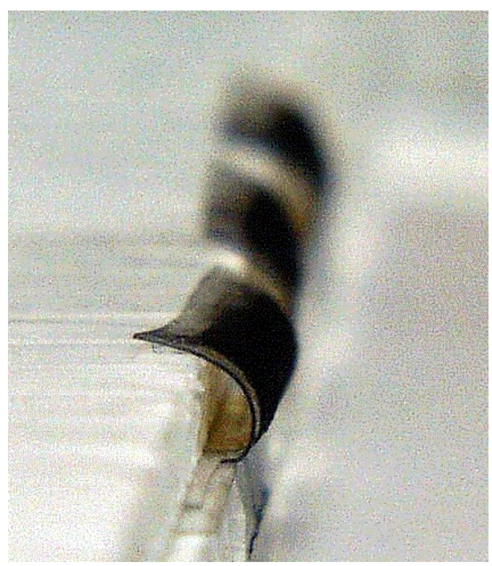

Figure 4. A unimorph flow control device.

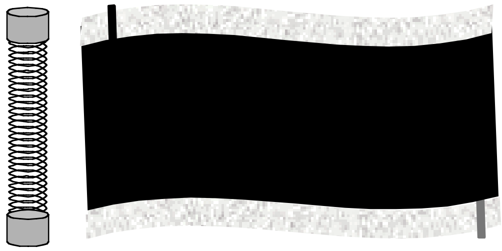

Figure 5. 1-DOF spring roll fabrication process.

Figure 6. 1-DOF spring roll.

One version of this roll was able to stretch from an initial length of 76 mm to 89 mm, a strain of 17%. The strain of the active region only (i.e., not including the end caps) was 26%. The available blocked force was 14 N (3.2 lbf) for this 18 g actuator.

A variation on the 1-DOF roll is the 2-DOF roll, in which multiple electrodes are patterned onto the film (see Figure 7). Each electrode activates half of the actuator (along the axis). When one electrode is activated, that side elongates compared with the other, causing the actuator to bend much like a bimorph, as shown in Figure 8. When both electrodes are activated, the actuator extends much as a 1-DOF spring roll.

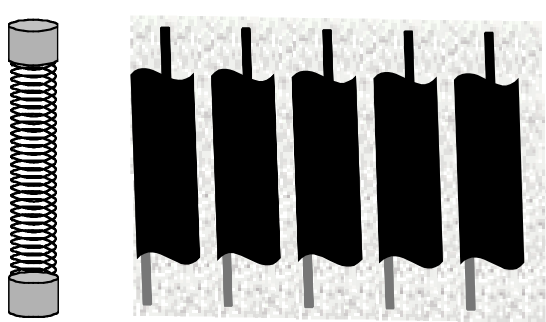

Figure 7. 2-DOF spring roll fabrication process.

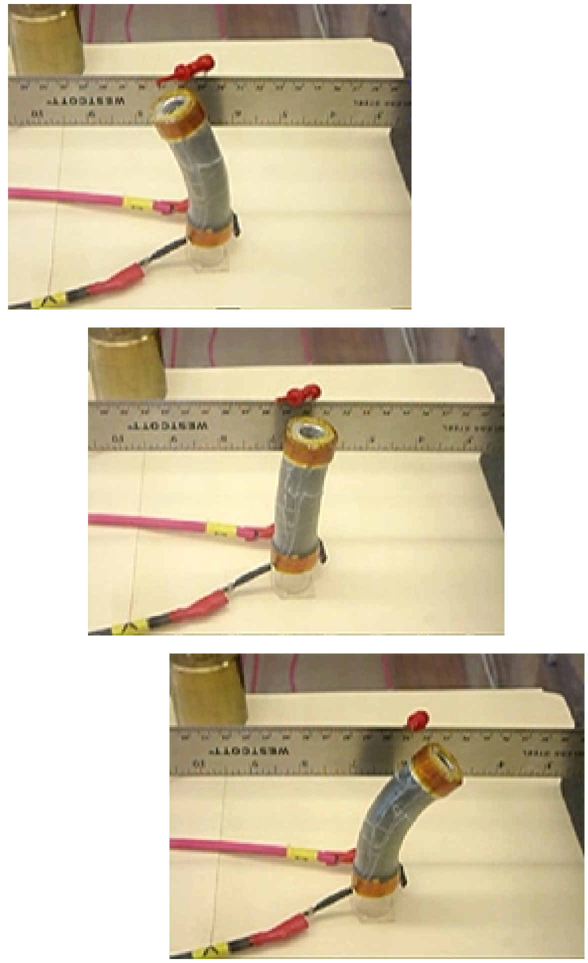

Figure 8. Video stills of a 2-DOF spring roll undergoing bending.

These rolls have demonstrated the ability to bend 90 degrees and provide a blocked lateral force of 0.7 N. Another variation can bend 60 degrees and provide 1.68 N of lateral force.

The logical next step after the 2-DOF roll is the 3-DOF roll, whereby separate electrodes are patterned not over each half of the roll, but over each quarter (radially), allowing the roll to be bent on two independent axes as well as being extended axially. This has been demonstrated in the lab in the form of a joystick controlled camera.

It is worth noting that spring rolls (and in fact all of the dielectric elastomer actuators) share some common features:

- Their response is proportional to the square of the applied voltage, unlike the “bang-bang” response of pneumatics, hydraulics, and solenoids.

- Since the method of activation is capacitive, there is no penalty for DC operation. That is, unlike an electromagnetic motor, there is no current being drawn when "stalled."
- Similarly, EPAM can operate across the frequency spectrum. As a speaker, it can operate up to ultrasonic ranges (40+ kHz) or down to DC. Spring rolls have demonstrated a –3 dB rolloff (i.e., half their DC strain) at up to 70 Hz.

EPAM as an "Artificial Muscle"

We refer to EPAM as an "artificial muscle" because it shares many qualities with, and operates in mechanical regimes similar to natural muscle. Figure 9 shows that dielectric elastomers and natural muscle fill the "actuator gap" between other actuation technologies.

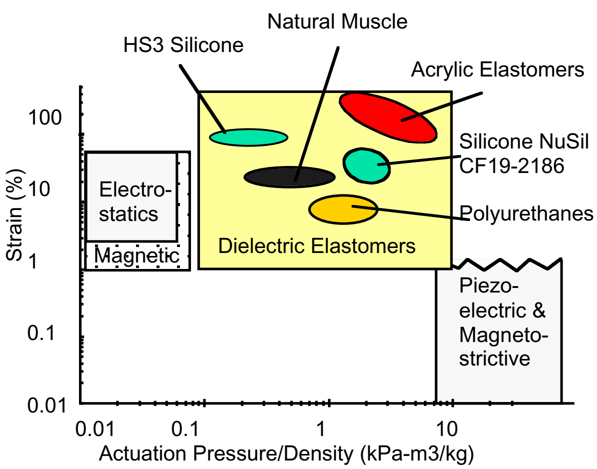

Figure 9. Dielectric elastomers fill the "actuator gap."

EPAM also shares other desirable features with natural muscle: Its operation is silent, and it can be cycled at frequencies above or below the audible range.

Actuators based on these materials can meet or exceed the strain, energy density, speed of response, peak power, and mechanical impedance of natural muscle [Meijer et al., 2001; Kornbluh et al., 2002]. Strains of more than 100% and energy densities of more than 3.4 J/g have been demonstrated in dielectric elastomers—more than 100 times those of electromagnetic devices [Pelrine et al., 2000]. Because of this high energy density, large strain, and fast speed of response, dielectric elastomers can be used as direct-drive elements much like natural muscle.

EPAM is also compliant, which not only makes it back drivable, but also reduces the need for complex feedback control. And much like natural muscle, it is scale invariant. Just as natural muscle operates similarly across the animal kingdom (from insects to elephants), dielectric elastomers lend themselves to micro machines as well as large mechanisms.

EPAM can also absorb energy as muscle can. Just as the film moves when voltage is applied, deforming the film will cause a voltage across the electrodes. This "motor/brake" function can be used to generate energy, or as a sensor.

EPAM lends itself to three primary areas of application for underwater robotics: propulsion, maneuver, and power generation.

Propulsion. EPAM has three potential roles in the field of underwater propulsion. EPAM can (1) enhance traditional methods of propulsion, (2) replace individual components used by these methods, or (3) enable new forms of propulsion.

The most ubiquitous form of underwater propulsion is the propeller. Most propellers have fixed blades, with peak efficiencies at a specific frequency. Even variable pitch propellers are efficient only in one direction. The addition of an adjustable surface or foils on the blade could tune the efficiency of the propeller as necessary, and potentially reduce cavitation. EPAM could act as this surface due to its high strain and energy density. Flow control measures that have been built include the unimorphs described previously, as well as diaphragm arrays, as shown in Figure 10.

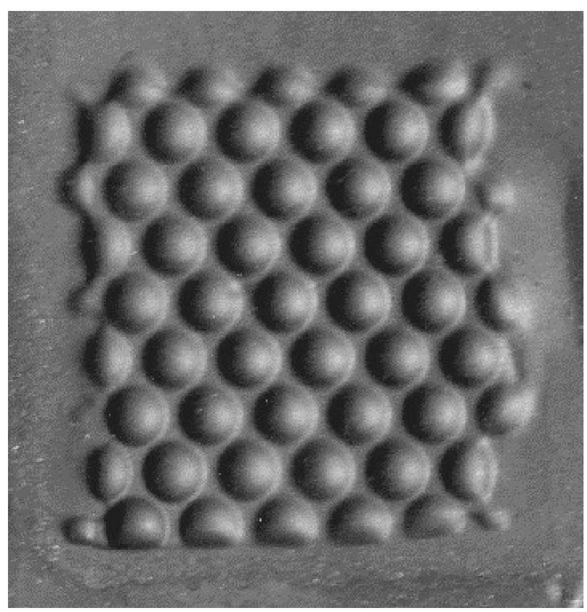

Figure 10. An array of diaphragms on an EPAM film.

EPAM has also been demonstrated turning various shafts to make electric motors, as shown in Figure 11. This could replace the motors typically used to turn propellers, and there are several reasons to consider this. Traditional motors operate best at high speeds, and need to be geared down for efficient operation. This results in noisy, heavy, complex systems that require more cost and buoyancy compensation. Moreover, motors are only efficient when operated at a constant speed. If an underwater vehicle needs to maneuver frequently (e.g., in the littorals), energy is used at a significantly higher rate, reducing efficiency. EPAM motors, on the other hand, can be efficient across a wide range of speeds without gearing, resulting in simpler and lighter systems with longer mission times.

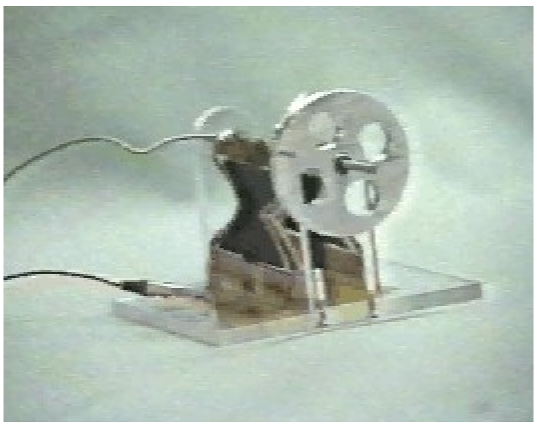

Figure 11. An EPAM enabled motor.

However, UUVs driven by propellers of any kind have some inherent shortcomings, many of which are exacerbated in very shallow water (VSW) and the surf zone (SZ):

- They have poor maneuverability in tight places, especially in the currents and surges associated with VSW and the SZ. Sleek torpedo-like designs with a rear-mounted propeller are limited in their ability to execute small diameter turns. Designs with multiple thrusters are generally larger, limiting their ability to navigate through obstacles, utilizing too much of the limited power in batteries, and becoming subject to wave surges.
- They are not particularly stealthy, thus limiting their survivability. Hard exteriors, motors, and propellers provide a significant acoustic signature. Inorganic surfaces and wakes increase the chances of visual or radar detection. Ferrous components and motors provide a magnetic source for detection.
- Propulsion by propellers, fans, and hydrodynamic surfaces is easily fouled by sand, rocks, and oceanic vegetation, thus further limiting potential areas of effectiveness for these systems.

In response to the limits of propellers, EPAM enables novel propulsion methods that do not lend themselves to traditional actuator technologies.

Some of the most striking examples of this method are terrestrial biologically inspired robots that have been built and operated using the spring roll actuators. These robots, built under contract with DARPA and ONR, are shown in Figures 12 through 14.

Flex [Eckerle et al., 2001], the largest of the robots at 470 g, was the first self-contained walking robot powered by electroactive polymers. Flex can move at speeds greater than 12 cm/s, actuating its legs at over 10 Hz.

Skitter [Pei et al., 2002] was designed under DARPA's Synthetic Multifunctional Materials (SMFM) program to demonstrate the ability of EPAM to act not only as an actuator, but also as the structure of a robot. This particular robot is based loosely on Stanford University's Sprawlita robot, which uses pneumatic actuators in a similar fashion. In spite of its simple design, Skitter demonstrated a speed of 6.8 cm/s.

MERbot [Pei et al., 2003] (which gets its name from the Multifunctional Electroelastomer Rolls that form its legs) is the next logical step, using 2-DOF rolls as flexible legs in lieu of discreet hip or knee joints. This robot has traveled at upwards of 14 cm/s. We are currently working on a MERbot that uses the 3-DOF spring rolls to eliminate the need to rotate in place.

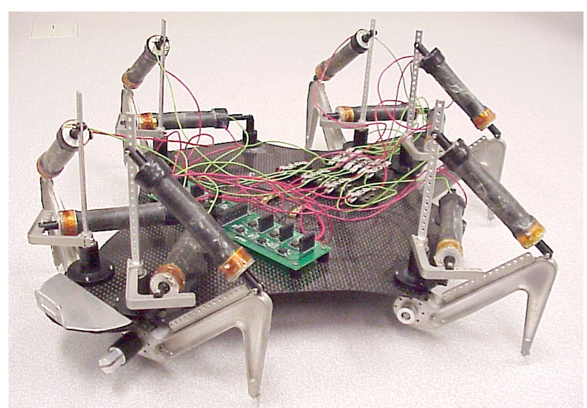

Figure 12. Flex.

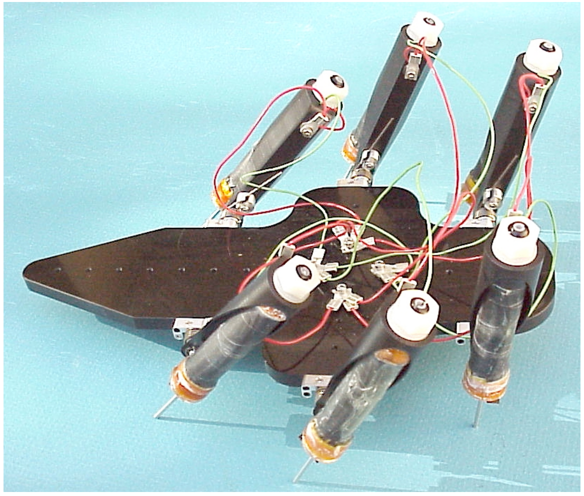

Figure 13. Skitter.

Figure 14. MERbot.

Another design under consideration is a snake robot, which brings us into the realm of underwater robotics (consider the similarity between snakes and eels, and the fact that some species are capable of traversing both land and water). Such a robot could be manufactured by concatenating several 3-DOF rolls. SRI has demonstrated a proof-of-concept snake segment. A CAD conceptual representation is shown in Figure 15.

Snake robots are challenging from both a mechanical and a control perspective. Mechanically, snakes are highly articulated structures that are compact and lightweight and interact energetically with their environments, due to their friction, strength, and stiffness at many points on their bodies. Indeed, these interactions are their means of locomotion. From a control perspective, snakes must be able to coordinate their large numbers of segments (biological snakes can possess more than 300 vertebral segments) and man-

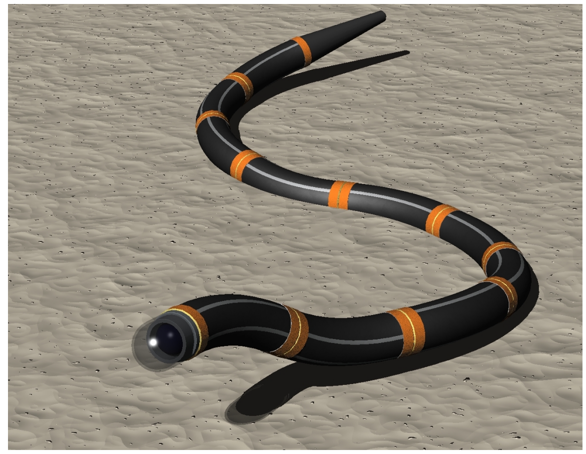

Figure 15. CAD representation of a snake robot made from 3-DOF spring rolls.

age force interactions with their environments to produce useful and adaptive gaits and behaviors.

Snake robots based on conventional actuation technologies such as electric motors cannot overcome these challenges. Electric motors must be used in conjunction with high-gear-ratio transmissions that produce high rotational speeds that maximize the power output. Several researchers have developed robots driven by electric motors using highly geared rotary joints [Chirikjian and Burdick, 1995; Yim, Duff, and Roufas, 2000]. The specific power of the best (and most expensive) electric motors does not generally exceed 0.5 W/g. When the mass of the gear box and mechanisms required to produce the 2-DOF motion required at each joint is included, the effective specific power density of the actuation mechanism is less than 0.05 W/g. In contrast, natural muscle can produce peak power of more than 0.2 W/g. The high ratio transmissions and stop-and-start motions typically used with electric motor drives in robot snakes result in relatively slow and inefficient motion. Electric motors can operate at high efficiencies when rotating at constant velocity and at high speeds. However, at slow speeds and with numerous accelerations and decelerations their efficiency is typically well below 25%.

The mechanical complexity of the joint mechanisms limits the number of DOFs that can practically be implemented in a robot. Further, electric drives are not easily back drivable and are therefore incapable of the viscoelastic dynamic motion of biological snakes and eels. Duplicating the viscoelastic behavior of the snake is critical for increasing the mobility and the efficiency of locomotion, as well as simplifying the control. Like most animals, snakes are dynamically "tuned" systems. The stiffnesses and bending modes of the snake body determine the most efficient frequencies and amplitudes of the waves involved in the different gaits [Alexander, 1988].

Observations of biological snakes further illustrate the role of compliance (flexibility) in enhancing their mobility. A snake's body wall bends and rotates considerably when transmitting propulsive force to external sites of resistance [Gasc et al., 1989; Jayne, 1988a,b; Moon and Gans, 1998].

Elastic mechanisms also provide a means of stabilizing motion (and therefore simplifying control), especially during sudden perturbations such as those due to slippage or sudden contact with objects. This stabilization also uses the ability of muscle to provide a damping or braking function (due to its inherent viscoelastic damping and properly timed force application). These inherent disturbance rejection mechanisms have been termed "preflexes," since they use passive mechanical mechanisms to bypass even the most rudimentary feedback loops of reflexes [Brown and Loeb, 1996].

Existing electric-motor-based snake robots (particularly those of Yim, Duff, and Roufas [2000]) have successfully negotiated a variety of terrains and obstacles (including climbing with hooks) attesting to the mobility of snakes. However, they are slow and energy inefficient and unable to adapt to unknown or random terrain features. Other researchers have more successfully reproduced dynamic snakelike locomotion using electric motors [Hirose, 1993; Miller, 2002]. However, these snakes are limited to operation in a horizontal plane (thereby reducing the importance of actuator weight) and therefore cannot negotiate vertical obstacles or various terrains (in fact, they utilize wheels to provide directional frictional contact). Clearly, an actuation technology that can duplicate the motion, high peak power and viscoelastic behavior of natural muscle is needed. Other efforts to reproduce musclelike actuation in snakelike robots have used shape-memory alloy actuation (e.g., Wilbur et. al, 2002). As thermal actuators, however, shape-memory alloys are energy inefficient (typically 2% or less) and have slow response speeds in air. Hydraulics or pneumatics could produce musclelike actuation but would require a pump as well as complex valving and hosing. The use of motors and pumps also adds undesirable noise that can limit stealth.

Rajiform motion is another propulsion technique that EPAM is uniquely qualified to produce. This could take the form of the ray-inspired UUV shown in Figure 16.

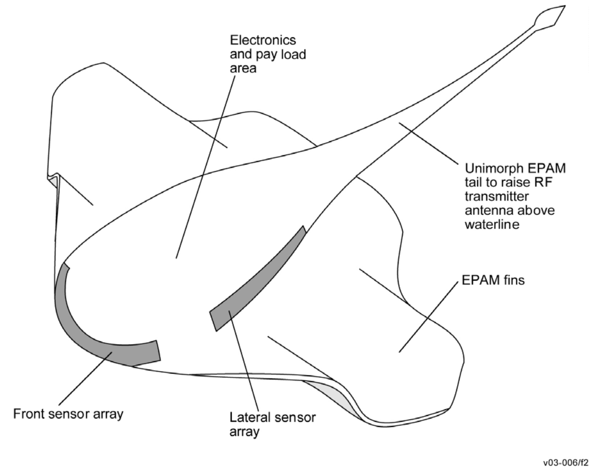

Figure 16. Concept for a ray-inspired UUV enabled by EPAM.

This "Raybot" would be highly maneuverable, able to rotate in place or travel backward. Its flat shape would be less susceptible to turbulence (especially if its sits just above the ocean floor as shown in Figure 17), and would also afford more space for sensors or other payloads.

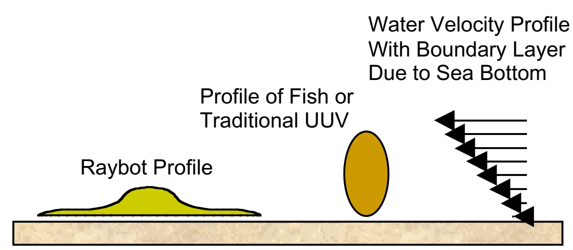

Figure 17. A "Raybot" is subject to lower disturbing hydrodynamic forces where boundary layer effects are important at the ocean bottom.

Actuation needs are a significant challenge to the creation of rajiform motion:

- It should be distributed in nature. Force has to be applied in a nonuniform, oscillatory manner over a large area. Also, a distributed system is robust and fails gracefully via gradual degradation as opposed to failing suddenly and catastrophically.
- It should be flexible. Rajiform motion is inherently fluid and involves significant flexing of the fin. While such motion might be approximated with joints, tendons, and the like, this would introduce additional weight and complexity. Additionally, an actuator should be back drivable and compliant, as the UUV may come into sudden contact with various obstacles, and it would be preferable for the UUV to deform locally instead of being thrown off course.

- It should be efficient. This means a high power-to-weight ratio with few losses.
- It should operate at speeds from 1 to 10 Hz, with deflections of several centimeters over a half-meter length without gearing or mechanical amplification.

Traditional actuation methods are clearly inadequate for such motion. A previous effort to reproduce musclelike actuation in a rajiform robot (Robo-Ray, the product of a student project at the University of British Columbia) used shape-memory alloy, but this was found to be “inefficient and difficult to control” [Davis et al., 2002]. Hydraulics or pneumatics could produce musclelike actuation but would require a pump as well as complex valving and hosing. The use of motors and pumps also adds undesirable acoustic and electromagnetic signatures.

Dielectric elastomers, however, provide numerous options for creating a multiple-DOF undulating fin. We could use multiple 2-DOF spring rolls to create a fin as shown in Figure 18.

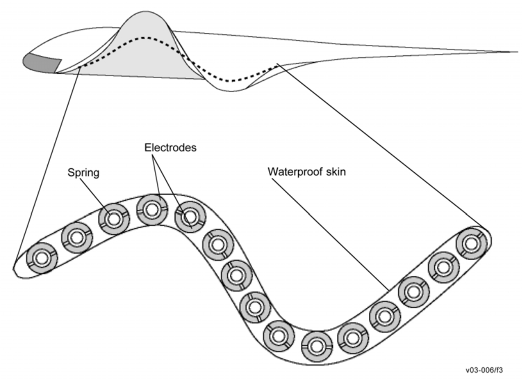

Figure 18. Spring roll fin section view.

While probably functional, and relatively easy to put together with current technology, this approach uses several discreet actuators that would increase the part count and need a wrapping or sheath to act as a skin.

Another approach would be to create a “planar roll,” a single actuator that would resemble a large oblong spring roll, as shown in Figure 19. Multiple electrodes on the top and bottom surface would act in antagonistic pairs to force a particular part of the fin up or down.

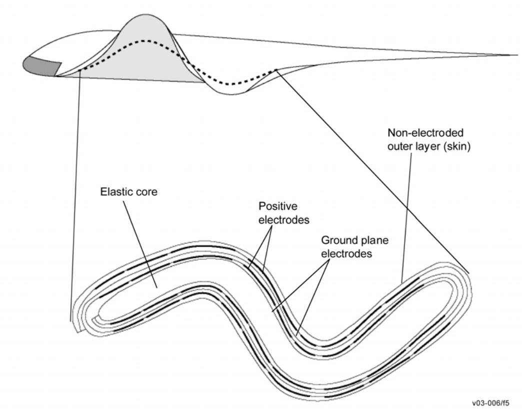

Figure 19. Planar roll section view.

A third option is a stacked film bimorph, which would bear some resemblance to the planar roll. However, instead of rolling the film around an elastic surface to create multiple layers, layers are attached one atop the other on a flexible—but nonelastic—substrate. The result is a thin substrate fin with stretched film in tension on either side. If the top film were to be activated, it would stretch, releasing tension, and causing the fin to bend down. However, in our case we would pattern the top and bottom electrodes in antagonistic pairs as shown in Figure 20, so that such bending would happen locally instead of over the entire fin.

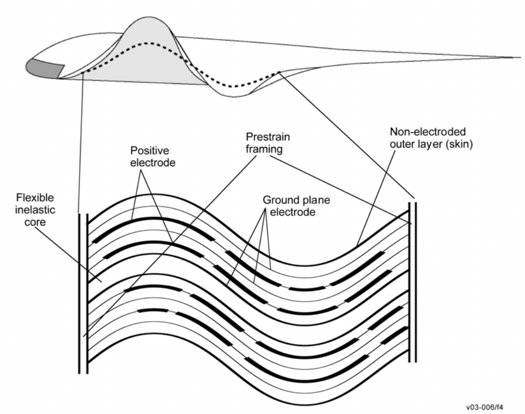

Figure 20. Stacked film bimorph section view.

EPAM could also enable other biomimetic propulsion technologies such as peristaltic movement, or jet propulsion as used by jellyfish and squid. In this capacity, EPAM makes use of its inherent compliance and the fact that it matches the mechanical impedance and density of water.

Maneuver. Closely related to propulsion, the ability to maneuver could also benefit from the use of EPAM. As with propulsion, EPAM can be used to augment or replace current technologies, or enable new ones.

Maneuvering is traditionally accomplished with thrusters or hydrodynamic planes. Since maneuvering thrusters are conceptually identical to the propellers used for propulsion, EPAM can be used on these devices in a fashion similar to that for propellers as described above.

Hydrodynamic planes could be made flexible and simplified by the use of EPAM, and might increase vehicle speed in addition to maneuverability. In addition, the surface texture of these planes could be dynamically changed for different boundary layer settings.

Such planes could be further developed into biomimetic maneuvering fins. Just as fins are used to propel fish, they are also used for maneuvering. For example, many fish use caudal (tail) fins for fast and efficient movement in the open water, but use pectoral (side) fins for fine maneuvering such as foraging.

2- and 3-DOF spring rolls made from dielectric elastomers could be tailored and shaped into effective maneuvering fins. In addition, the electrodes used for actuating the elastomers can be used as sensors to determine the position (the capacitance changes as the film deforms), and therefore forces upon a given fin. This can allow local closed loop control of certain fin motions.

Power Generation. Just as mechanical energy can be imparted on a motor to create a generator, mechanical deformation of EPAM causes an increase in energy that can be harvested for power. This mode has been demonstrated at specific energy densities up to 0.4 J/g. The heel-strike device shown in Figure 21 is able to produce 0.8 W of electrical power at an average walking speed.

A UUV which employs EPAM fins for maneuvering or propulsion could, when power reserves are low, anchor itself to the bottom and allow wave motion to recharge its batteries. This could also be used on fixed platforms.

While a traditional spinning generator could also serve this purpose, an EPAM generator could do so with a lower weight penalty, less noise, and in configurations that would be impractical with propeller-driven generators (e.g. large sheets as part of, or deployed by, the UUV to harvest wave motion). In addition, because natural energy sources often have variable and difficult to predict frequencies, EPAM

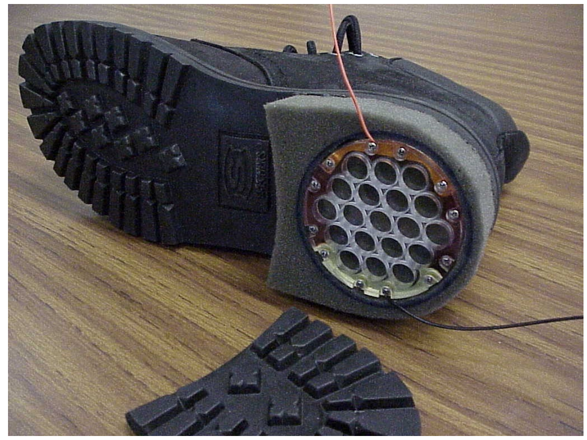

Figure 21. Heel-strike generator.

can better match the mechanical input due to its efficient operation over a wider bandwidth than electromagnetic generators. Dielectric elastomers also have greater strain and energy density than electrostrictive polymers such as PVDF.

Summary

Electroactive polymers made from dielectric elastomers have been successful in a diverse array of terrestrial applications, including pumps, speakers, generators, flow control, and notably robotics. This is not surprising given their high energy densities and efficiency. Considering EPAM's close match to water in terms of mechanical impedance and density, it is an excellent candidate for UUVs and other underwater applications.

Bibliography

Alexander, R. 1988. *Elastic Mechanisms in Animal Movement*, Cambridge University Press, Cambridge.

Ayers, J. Davis, and A. Rudolph, MIT Press, pp. 271–284.

Baughman, R.H. et al. 1999. *Science*, Vol. 284, p. 1340.

Brown, I.E., and G.E. Loeb. 1999. "A Reductionist Approach to Creating and Using Neuromusculoskeletal Models," in *Biomechanics and Neural Control of Movement*, ed. J.M. Winters and P.E Crago, Springer-Verlag, New York.

Chirikjian, G.S., and J.W. Burdick. 1995. "Kinematically Optimal Hyper-Redundant Manipulator Configurations," *EEE Trans. Robotics and Automation*, Vol. 11, pp. 794–806.

Davis, H., R. Boileau, L. Fan, and T. Moore. 2002. "Mechanization of Rajiform Swimming Motion: The

Making of Robo-Ray," student project, University of British Columbia Engineering Physics Project Laboratory (January).

Eckerle, J., S.E. Stanford, J.P. Marlow, R.H. Schmidt, S. Oh, T.P. Low, S.V. Shastri. 2001. "A Biologically Inspired Hexapedal Robot Using Field-Effect Electroactive Elastomer Artificial Muscles," in *Proc. SPIE 8th Annual Symposium on Smart Structures and Materials 2001: Industrial and Commercial Applications of Smart Structures Technologies*, Vol. 4332, San Diego, California (April).

Gasc, J.P., D. Cattaert, C. Chasserat, and F. Clarac. 1989. Propulsive Action of a Snake Pushing Against a Single Site: Its Combined Analysis," *J. Morph.,* Vol. 201, pp. 315–329.

Hirose, S. 1993. *Biologically Inspired Robots: Snakelike Locomotors and Manipulators*, Oxford U. Press.

Jayne, B.C. 1988a. "Muscular Mechanisms of Snake Locomotion: An Electromyographic Study of Lateral Undulation of the Florida Banded Water Snake (Nerodia fasciata) and the Yellow Rat Snake (Elaphe obsoleta)," *J. Morph*., Vol. 197, pp. 159–181.

Jayne, B.C. 1988b. "Muscular Mechanisms of Snake Locomotion: An Electromyographic Study of the Sidewinding and Concertina Modes of Crotalus cerastes, Nerodia fasciata, and Elaphe obsolete," *J. Exp. Biol*., Vol. 140, pp. 1–33.

Kornbluh, R et al. 1999. *Proc. SPIE*, Vol. 3669, p. 149.

Kornbluh, R., R. Full, K. Meijer, R. Pelrine, and S. Shastri. 2002. "Engineering a Muscle: An Approach to Artificial Muscle Based on Field-Activated Electroactive Polymers," *Neurotechnology for Biomimetic Robots*, eds. J. Ayers, J. Davis, and A. Rudolph, MIT Press, pp. 137–172.

Meijer, K., M. Rosenthal, and R. Full. 2001. "Muscle-like Actuators? A Comparison Between Three Electroactive Polymers," *Smart Structures and Materials 2001: Electroactive Polymer Actuators and Devices*, ed. Y. Bar-Cohen; Proc. SPIE, Vol. 4329, pp. 7–15.

Miller, G. 2002. "Snake Robots for Search and Rescue," *Neurotechnology for Biomimetic Robots*, eds. J.

Moon, B.R., and C. Gans. 1998. "Kinematics, Muscular Activity and Propulsion in Gopher Snakes," *J. Exp. Biol*., Vol. 201, pp. 2669–2684.

Park, S. and T. Shrout. 1997. *J. Appl. Phys.*, Vol. 82, p. 1804.

Pei, Q., R.E. Pelrine, S.E. Stanford, R.D. Kornbluh, M. Rosenthal, K. Meijer, R.J. Full. 2002. "Multifunctional Electroelastomer Rolls and Their Application For Biomimetic Robots," in *Proc. SPIE, Smart Structures and Materials 2002: Industrial and Commercial Applications of Smart Structures Technologies*, ed. Y. Bar-Cohen, Vol. 4698, San Diego, California (March).

Pei, Q., M. Rosenthal, R.E. Pelrine, S.E. Stanford, R.D. Kornbluh. 2003. "Multifunctional Electroelastomer Roll Actuators and Their Application for Biomimetic Walking Robots," to be published in *Proc. SPIE, Smart Structures and Materials 2003: Electroactive Polymer Actuators and Devices (EAPAD)*, ed. Y. Bar-Cohen, San Diego, California (March).

Pelrine, R.E., Kornbluh, R.D., Joseph, J.P. 1998. "Electrostriction of polymer dielectrics with compliant electrodes as a means of actuation," *Sensors and Actuators A-Physical,* Vol. 64, pp. 77-85 (January).

Pelrine, R., R. Kornbluh, Q. Pei, and J. Joseph. 2000. "High-Speed Electrically Actuated Elastomers with Over 100% Strain," *Science*, Vol. 287, No. 5454, pp. 836–839.

Wilbur, C., W. Vorus, Y. Cao, and S. Curie. 2002. "A Lamprey-Based Undulatory Vehicle," in *Neurotechnology for Biomimetic Robots*, eds. J. Ayers, J. Davis, and A. Rudolph, MIT Press.

Yim, M., D. Duff, and K. Roufas. 2000. "PolyBot: a Modular Reconfigurable Robot," *Proc. IEEE Intl. Conf. on Robotics and Automation (ICRA),* San Francisco (April).

Zhenyi, M., J.I. Scheinbeim, J.W. Lee, B.A. Newman. 1994. "High-Field Electrostrictive Response of Polymers," *J. Polym. Sci. B Polym. Phys*, Vol. 32, p. 2721-2731 (December).