1. EPAM Background

Many types of candidate electroactive materials have been or currently are under investigation, including single-crystal piezoelectric ceramics and carbon nanotubes. Electroactive polymers (EAPs), such as those developed by SRI, are of particular interest because of the low cost of the materials and the ability of polymers to be tailored to particular applications. Piezoelectric polymers such as PVDF have been known for many years. This material has found some non-robotic applications, but for robots PVDF has a relatively low power and energy density. More recently, many other types of polymers have been investigated. Electrochemically actuated conducting polymers and gels, sometimes referred to as ionic polymers, use chemical changes driven by low voltages to actuate. Examples include conducting polymers and IPMC. These polymers are attractive because of their low voltage operation and good actuation pressures, but are limited for robotic applications because of their relatively slow speeds and low efficiency.

Another category of electroactive polymers are sometimes referred to as electronic EAPs. This category includes EPAM as described below, and also electrostrictive polymers [1], which change dielectric constant as part of the actuation mechanism. Electrostrictive polymers have comparable performance to many types of EPAM, but are typically stiffer and have lower strains. In general, electronic EAPs require much higher voltages than ionic EAPs, but they can be fast, efficient, and have high energy output.

Starting in the early 1990s, SRI invented a new type of electroactive polymer, known variously as EPAM, dielectric elastomers, or electroelastomers. It has been well known for many years that the electric field pressure from free charges on the surface of all insulating materials induces stress (Maxwell’s stress) that strains the material. Previously, Maxwell stress was regarded as a nuisance effect on piezoelectrics, but when applied to softer polymers with high breakdown voltages, the mechanical output can be substantial. The basic element of EPAM actuators is a dielectric polymer film, typically 10 to 200 [µm] thick, that is coated on each side with a compliant electrode material such as carbon-impregnated elastomer. Normally the polymer is an elastomer for highest strains, but non-elastomer polymers can also produce significant actuation. When a voltage is applied across the two electrodes, the electrostatic forces compress and stretch the film. As shown in Fig. 1, the compression of the film thickness brings opposite charges closer together, whereas planar stretching of the film spreads out or separates similar charges. Both changes 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 are greater than that of any other known high-speed electrically actuated material (i.e., material actuated at a bandwidth above 100 [Hz]). Dielectric elastomers also have other desirable material properties.
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such as good actuation pressures and high theoretical efficiencies (80 to 90%) because of their low viscoelastic losses and low electrical leakage. In addition, 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 [2]. As can be seen in Fig. 2, dielectric elastomers not only outperform existing actuator technologies in various areas but also are similar to natural muscle in that they fill the “actuator gap” between other actuation technologies.

2. Desired Properties of New Robot Actuators

Some of the key desired features for new robotic actuators (whether polymer or other types) include the following:

- Totally quiet operation: This is important for noise-sensitive applications such as in hospitals, home robots, and stealth for military or law enforcement robots.
- Variety of shapes and sizes, from cylindrical, like many skeletal muscles, to flat, such as proof-of-principle EPAM devices that can travel under doors.
- High power density and high peak power density, to enable rapid dynamic motions such as those used in hopping, jumping, or running to surmount obstacles or for high speed maneuvers.
- Inherent springlike compliance, to enable energy to be stored for efficient locomotion and adaptation to uneven terrain or cluttered workspaces. Natural creatures use the compliance of muscles and tendons to create oscillatory systems that locomote efficiently. Unlike highly geared motors, the joints should be back drivable to adapt to uneven terrain or easily recover from collisions.

- High efficiency in power conversion: Many future robot applications require mobility with onboard power supplies, requiring high efficiency actuation.
- Multifunctionality: The ability to use a single device for multiple functions such as multiple degrees of freedom (DOF) in a single actuator or combining structural and actuator functions or combining actuation and sensing.

3. First Generation of EPAM-Enabled Robots

In seeking to create robots that embody the advantages discussed above, we have built many first-generation prototypes. Some of the most striking examples are biologically inspired robots that use cylindrical “spring roll” actuators made from dielectric elastomers. These robots are shown in Fig. 3. A spring roll actuator consists of electroded elastomer film wrapped around a spring. When an applied voltage actuates the film, the spring extends axially, creating a 1-DOF spring roll. By patterning multiple electrodes on the film, one can also make an actuator that can bend in multiple directions, creating 2- or 3-DOF spring rolls.

Flex [3], the largest of the robots at 470 [g] mass and 36 [cm] length, was the first self-contained (i.e., battery powered) walking robot powered by electroactive polymers (Fig. 3 (a)). A second version of this robot used two 1-DOF spring rolls for each of its six legs, one actuator to lift and lower the leg, and the other actuator to move it forward and back [4]. Like the two robots described below (and most insects), Flex walks with a “dual tripod” gait in which the left front, left rear, and center right legs move up, down, forward, and back together. Flex can move at speeds greater than 12 [cm/s], actuating its legs at over 10 [Hz].

Skitter [5] was designed to demonstrate the ability of EPAM to act not only as an actuator but also as the structure of a robot as a first step in multifunctionality (Fig. 3 (b)): This particular robot is based loosely on the Sprawlita robot [6], which uses pneumatic actuators in a similar fashion. Each of the six legs points a single 1-DOF actuator down and slightly backward, and is attached to the body on a compliant joint. In spite of its simple design, Skitter has demonstrated a speed of 6.8 [cm/s].

MERbot [7], which gets its name from the Multifunctional Electroelastomer Rolls (MERs) that form its legs, is the next logical step, using 2-DOF rolls as flexible legs
Fig. 3 Biologically inspired EPAM-powered robots (Movies are available at http://www.erg.sri.com/video.html)

Fig. 4 Proof-of-principle jumping EPAM device

Fig. 5 Conceptual design of an EPAM-based snake robot

in lieu of discrete hip or knee joints (see Fig. 3 (c)). The MERs yield a very light, simple robot that still has a high degree of dexterity. MERbot has traveled faster than 14 [cm/s].

Jumping robots are also attractive with EPAM, and this application illustrates the advantages of high energy direct drive actuation. Fig. 4 shows an early jumping EPAM platform [7]. Note from Fig. 4 the potential simplicity of a jumping robot EPAM design. This design uses only three EPAM diaphragm actuators. Electric motors have difficulty generating the high peak power density necessary for jumping starting from a stopped state, so electric motor jumping drives typically require gearboxes and energy storage in a spring with a sudden release mechanism.

4. Future Generations of EPAM-Enabled Robots

One design under consideration is a snake robot, which could be manufactured by concatenating several 3-DOF rolls (see Fig. 5). SRI has demonstrated proof-of-concept snake segments. Snake robots are challenging from both a mechanical and a control perspective. For snakes and tentacle-type robots, besides offering performance advantages, the simplicity and multifunctionality of EPAM is a major advantage because of the number of DOF required.

Electric motors are typically used for snake robots [8] [9]. However, because of the need for gear transmissions to reach desired torques, overall power density is typically low, with estimates of 0.05 [W/g] compared with 0.1 to 0.2 [W/g] for natural muscle. Electric motors are also inefficient in the start-stop mode needed for snake mobility. Other efforts to reproduce musclelike actuation in snakelike robots have used shape-memory alloy actuation [10], but again these snake robots are slow and inefficient.

EPAM is also uniquely qualified to produce finlike motion, including the rajiform motion used by skates and rays. A swimming “Raybot” (Fig. 6) would be highly maneuverable and able to rotate in place or travel backward. Its flat shape would be less susceptible to turbulence and would also afford more space for sensors
or other payloads. 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 a shape memory alloy, but this material was found to be "inefficient and difficult to control" [11].

EPAM could also enable other biomimetic propulsion technologies such as peristaltic movement, or jet propulsion such as that used by jellyfish and squid. The latter application would exploit the inherent compliance of EPAM and the fact that it matches the mechanical impedance and density of water.

Dielectric elastomers are also attractive for flapping-wing flight (see Fig. 7); in fact, various EPAM-powered flapping mechanisms have been manufactured and tested in the laboratory [12]. These flapping mechanisms have not yet produced the continuous power necessary for self-contained sustained flight, because of excessive structural mass for the actuator (the EPAM fraction was only about 10% in tests to date) but they do show the ability for a very simple structure that can use resonance to achieve high flapping amplitudes at high power densities.

5. Summary and Conclusions

Electroactive polymer artificial muscles based on dielectric elastomers have been successfully used in a diverse array of robotic applications. Several proof-of-principle robots have been demonstrated. We anticipate continued advances in robots based on EPAM, as it enables high performance in simple, low cost, multifunctional designs. Besides continuous improvement by research organizations, Artificial Muscle, Inc. (www.artificialmuscle.com) is making significant strides in the commercialization of EPAM in the areas of lower voltage, longer lifetime, and greater environmental operating ranges. This base technology development ensures future EPAM robot designs will enable more radical robot designs and functionality than might be envisioned today.

References

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