Artificial Muscles

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Abstract
Actuators based on polymer materials can be constructed on both micro and macro scales. The principles of three types of polymer actuators are discussed. For macroscopic robotic applications, a feasibility study concluded that actuators based on conducting polymers and dielectric elastomer actuators fulfil the requirements for dextrous robotic grippers.

Introduction
Polymers form an alternative to materials commonly used for actuators in adaptive structures: Piezoelectric materials, Shape memory Alloys, Magnetostrictive materials and electrorheological fluids. The actuator known for the longest period by man - the striated muscle - is build from bio-polymers. One of its most surprising features is its scalability: An elephant is driven by the exact same actuator as an ant. This indicates that there is good reason to investigate the feasibility of polymer actuators in various areas.

We have studied polymer actuators for macroscopic applications, but their feasibility has more often been demonstrated for mini- or micro-applications. Two classes of polymers are commonly utilised: polymeric gels and electron-conductive polymers. A third class of polymers showing an electrostrictive response is equally promising. The principles and mechanisms of polymer materials with actuator properties are outlined in the following.

Research on polymer based actuators is a relative young discipline. It dates back to early work by Kuhn and Katchalsky in the fiftieth[1], but progress has especially been obtained from 1980 to date. A survey performed in 1996 of the research on polymer actuators identified approximately twenty groups in Japan, Europe, United States and Australia.

In Denmark, a group with participants from the Technical University of Denmark, Risø National Laboratory and the major industrial company Danfoss A/S has studied polymer actuators since 1996.[2]
The focus originally was the feasibility of polymer based actuators for robotic applications. The project called "ARTMUS - Artificial Muscles" now aims at developing a novel class of electrically controlled actuators based on polymer materials. Such an actuator must be based on low price materials, act linearly with smooth movements that allow for integrated feedback and control and show a performance as required by a dextrous robotic gripper: Lifting 0.1 kg over 1 cm in 0.1 s. Some of the analysis and conclusions from previous work are stated below.

Principles of polymer actuators
Polymer gels are crosslinked polymer chains swollen in a solvent. They often respond by a change in volume to changes in environmental parameters like temperature, solvent composition and electric fields. Basically the equilibrium between gel and the solvent is disturbed by these changes. A drastic volume change in a polyelectrolyte gel in response to changes in pH is illustrated in figure 1.

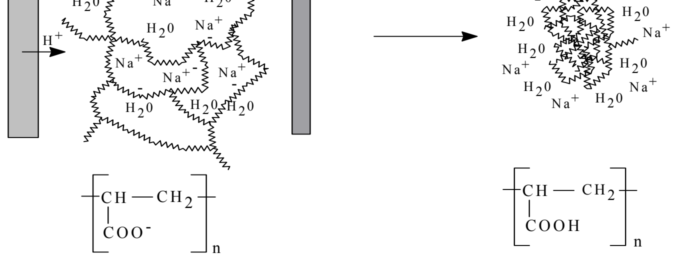


Figure 1. Polymeric system with actuator properties.
Partly ionised poly(acrylic acid) swollen in aqueous solution will contract strongly in acidic solution. Flexible electrodes made from conducting polyaniline (PAni) may produce the necessary change in pH.

Conducting polymers (e.g. polypyrrole and polyaniline) originally attracted attention because of their very large electronic conductivities (in special cases comparable with Cu). The polymers contain a conjugated, often one-dimensional, backbone, and their properties usually depend crucially on being oxidised or reduced by the introduction of anions or cations as dopants associated with the chain.

The accommodation of ions in the polymer also has consequences for their mechanical properties. The creation of charged electronic species on the chain can change the stiffness and the length of the individual polymer chains, and the incorporation of the sometimes bulky counterions can increase the volume - especially when the ions are associated with co-intercalating solvent molecules. This opens the possibility for the reversible control of mechanical properties by the application of a voltage, and is the foundation for the interest in conducting polymers as electromechanical actuators. The process is illustrated in figure 2.

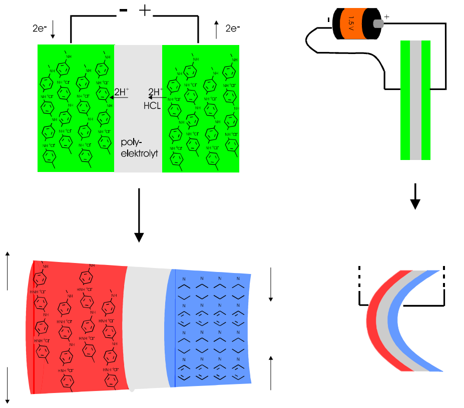


Figure 2. A bimorph based on the conducting polymer polyaniline (PAni). Both the macroscopic and molecular changes during operation are illustrated. Two polyaniline films are sandwiched around an ion-conducting film. As current flows, one side of the sandwich is reduced and the other oxidised. Concurrently, ions are transferred between the two sides leading to an expansion of the first and a contraction of the second side. The overall effect is a bending of the bimorph.

Electrostatic contraction of an elastic polymer film has proven to be a genuinely new approach to polymer based actuators.[3] From the phenomenological point of view, the actuators behave electrostrictively. Electrostriction is the second order term in the relation between strain and applied field. The first order term describes piezoelectricity. High electrostrictive coefficients have been measured in polymer gels[4] and in certain rubbers,[5] but the electrostatic actuator does not rely on materials showing electrostriction. The actuators are termed dielectric elastomer actuators. As illustrated in figure 3, they are formed by an elastic thin film sandwiched between two compliant electrodes. At sufficiently high electric fields, the elastic film is compressed by the electrostatic forces between the electrodes. Simultaneously, the actuator expands in the plane of the electrodes. It is possible to get a macroscopic response in these directions even for a film thickness as small as 1 micron, for instance by rolling a tube from the film (see figure 4).

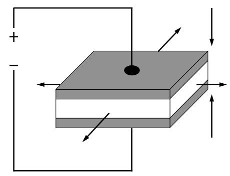


Figure 3: Dielectric elastomer actuator unit.

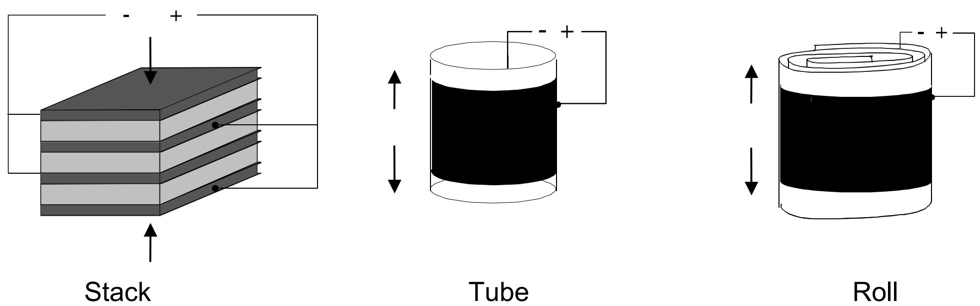
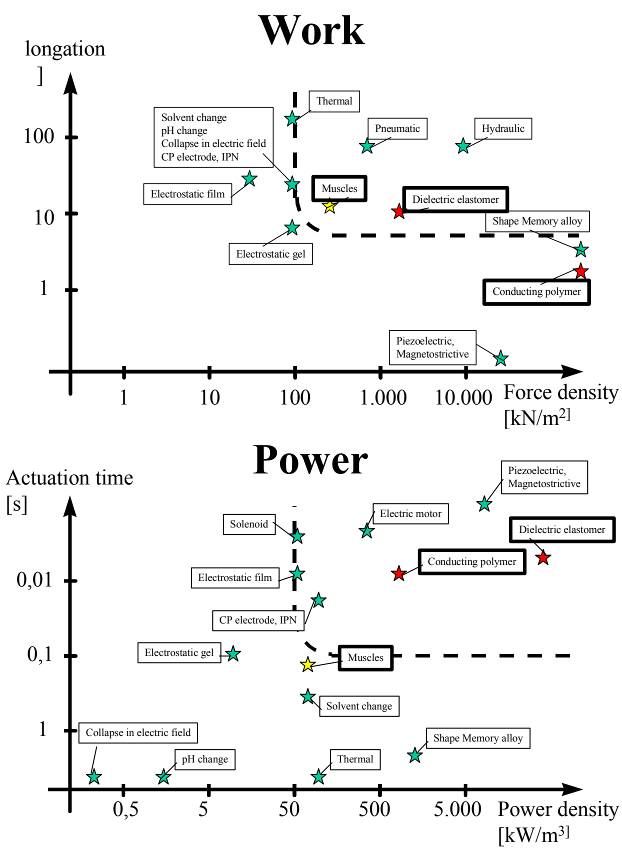


Figure 4. Actuator configurations. The stack actuator contracts whereas the tube and the roll actuator expand.

Performance of polymer actuators

Our feasibility study concluded that actuators based on polymer gel systems are limited in their response speed by diffusion processes. The activation of the actuator is caused by diffusion of a chemical signal or by heat, but the rate determining step is the contraction or expansion of the polymer network, which is a slow diffusion controlled process. As a result, we do not foresee actuators for macroscopic robotic application based on polymer gels. They do, however, have many other possible applications as actuators and for medical purposes, i.e. drug delivery systems and biomimetic energy-transducing devices as have been demonstrated by many Japanese groups[6] and European groups.[7] Actuators based on conducting polymers or dielectric elastomers, on the other hand, show basic performances fulfilling the requirements for robotic applications. Figure 5 illustrates the comparison of performances between different actuator types.

Figure 5. Performance of actuators. Polymer actuators are compared to conventional actuators (electric motors, hydraulics, pneumatics and solenoids) and alternative actuators (piezoelectric, SMA, magnetostrictive). For polymers and alternative actuators the specifications are basic materials specifications, not specifications for actual actuators build from the materials.
Force density is the maximum stress that the actuator can supply at no strain. Elongation is the maximum strain obtainable at no external load. Actuation time is the response time for full elongation.
The performances of conducting polymers, dielectric elastomers and natural muscles are marked on the figure. The dotted line indicates those performance specifications of interest for robotic applications should lie in the upper right part of the figure.



Relation to microactuators

So far conducting polymer microactuators have been demonstrated by Smela.[8] She uses micro-machine fabrication techniques to construct small boxes (300 μm x 300 μm sides) that close when activated and paddles driven by a hinge actuator of size (30 μm x 30 μm or smaller.[9]
Dielectric actuators are being developed by Pelrine, Kornbluh and Eckerle (SRI International) for very small robots (such as those that will fit in narrow pipes) and micro machines in general. That work is funded by the New Energy Development Organization (NEDO) of MITI of Japan and is connected to the Micro Machine Center (MMC).

Conclusions

Polymer based actuators have been demonstrated for micro applications. We investigate two technologies for macro-applications: Actuators based on conducting polymers and dielectric elastomer actuators. Both show materials performances that fulfil the requirements for an actuator driving a dextrous robotic gripper. Actuators based on polymer gels do not fulfil the requirements for speed and normally function only in an aqueous support medium. For that reason we do not investigate this technology all though it has many possibilities in other actuator areas and in medical applications.

References

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[2] The results from this collaborations is collected in three reports. The current article is based on these reports. Contributions to the reports have been given by:

Keld West and Steen V. Skaarup, Technical University of Denmark, Institute for Chemistry.
Ib Johannsen and Peter Sommer-Larsen, Risø National Laboratory, Cond. Mat. Phys. Chem. Dept.
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[9] Demonstrated on the Web-side:
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