Soft Actuation Technologies in Robotics and Challenges

Rohit Goyal[#]
Email-id:-rohitgoyals69@gmail.com
[#]*Jaipur Engineering College and Research Centre,*
Jaipur Rajasthan India

***Abstract*— This review paper comprises a detailed study of current methodologies for soft actuators, highlighting approaches suitable for small scale robotic applications. In this paper, I review the emerging nature inspired soft-bodied actuation systems, and in particular recent developments inspired by soft-bodied Animals.**

Incorporating soft technologies in actuation systems have potential to reduce the algorithmic and mechanical complexity. Special design challenges are presented by soft robots in that their sensing and actuation mechanisms owing to the highly integrated structure with the overall functionality. However, for small scale soft robotic actuation systems, in which they often lack sensing mechanism, computation, control and on-board power. Soft, active materials are particularly well suited for this task, which can be actuate with wide range of stimulants and demonstrating high motion complexities, large deformations and varied multi functionality. Incorporating of soft technologies in robotic system will also accelerate the evolution of robots that can safely interact with humans and natural environments. Recent research include both the development of new and composites materials that could be combined with multi-disciplinary fields to create hybrid systems for wide range of applications.

Keywords*—soft actuators, stimulants, soft technologies, composites, hybrid systems.

I. INTRODUCTION

In recent years, There has been growing interest in nature and natural principle as a source of inspiration for developing innovative technologies in various sectors by the robotic community. In order to try to understand and imitate animals capabilities the research into small-scale soft manipulators and stimuli responsive materials is flourishing. Animal manipulators such as elephant trunks, octopus arms, squid tentacles, and snakes have been widely considered as an inspiration for the development for the improvement of innovative soft robotic devices [1, 2].

In particular, Studying how animals use soft body part to move in complex, unpredictable environments can provide invaluable insights for emerging robotic applications such as medicine, search and rescue, disaster response, and human assistance [3]. In contrast to their rigid counterparts, soft actuator systems may easily deform and adapt to dynamic task settings and changing environments, be resilient to high loads [4], safe around humans and be compliant [5].

As the soft actuators decrease in size, they become considerable to the development of artificial muscles [6], cell scaffolds [7], micromanipulators [8,9], microrobots [10], microlenses [11], and smart transforming sheets [12], embedded with including diverse multi-functionality including drug delivery [13], sensing [14–16], biodegradability and biocompatibility [17,18].

The main advantage of such natural and compact systems is the compliance in the interaction, which provides adaptability to unstructured environments that can hardly be possible with conventional stiff structures [19].

Moreover, in applications which imply a high degree of flexibility, human interaction, safety and compliance are desirable features, the soft body actuators appears to be the right answer to these requirements.

In this review paper we introduce robotic actuator systems that are fundamentally soft and highly deformable. The scope of the paper is limited in several ways; mainly focus is on artificial materials. Furthermore, the focus is primarily on biomolecular, biohybrid muscle cells, or microorganism driven systems and methods that enable intrinsically soft actuators.

In the Section 2, we outline the field of soft miniature actuators, define key terminologies and give an introduction to the major classes of materials used. Next, we give a detailed overview of the different stimuli (thermal, light, pressure, chemical, and electric or magnetic fields) that pertain to these actuators (Figure 1) and challenges associate with these actuators.

We discuss the key biomechanical features of three soft bodies actuators that are used as inspiration for different soft robotic systems and suggest future directions where the soft actuators can be embedded with other technology for wide range of applications.

We close with a broader perspective recommending future research directions and applications.

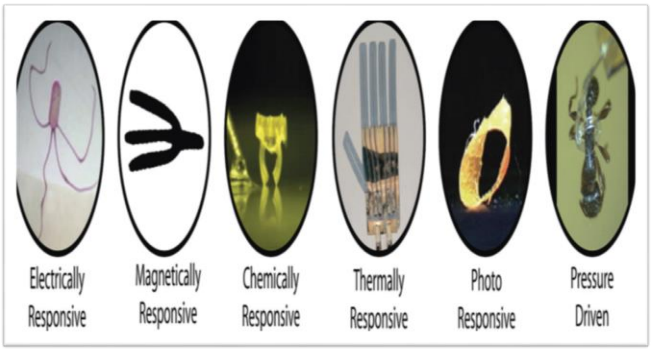

***Figure 1.** Examples of small soft robotic systems actuated with various stimuli. Systems include swimmers, jumpers, rollers, and manipulators. Electrically responsive*

II. Overview of Soft Actuation Technologies and Limitations

The selection of stimulant is critical for the soft actuators. Stimulus such as light, electric and magnetic fields are easy to accurately and rapidly modulate with respect to phase, frequency and magnitude. Most of the stimuli could also be applied remotely, which enables miniaturization down to the micrometer scale with no tether. One of the biggest challenges in soft robotics is designing flexible actuation systems capable of high forces, to replicate the functionality of muscles in the animal body. The ability of soft animals to change body shape depends on a large number of muscles being distributed over the body. **Table 1** gives a broad overview of what type of materials have previously been used with which type of stimulus.

Table 1. *A selection of soft materials and their demonstrated actuations stimuli*

	Electric field	Magnetic field	Pressure differential	Heat (electro-photothermal, etc.)	Light	Chemical (solvent water,pH, etc)
Polymers and gels	X	X	X	X	X	X
Conductive polymer	X					
Liquid-crystal polymers (LCPs), polymer networks (LCNs), elastomers (LCEs)	X			X	X	X
Ionic-polymer–metal composites (IPMCs)	X					
Dielectric elastomer actuators (DEAs)	X					
Shape-memory polymers (SMPs)				X	X	X
Hygromorphic polymer				X		X
Ferrogels and ferroelastomers						
Hydrogels	X	X	X	X	X	X
Fluids	X	X	X	X	X	X
Electrorheological fluid (ERFs)	X					
Magnetorhoelogical fluids (MRFs)		X				
Ferrofluids		X				
Dielectric fluids (electroconjugate fluids (ECFs))	X					
Liquid metals	X	X		X	X	X
Liquid marbles	X	X			X	X
Paper (cellulose)	X	X		X		
X						
Carbon	X		X	X		
Carbon nanotube (CNT) sheets, yarn	X		X	X		
CNT aeroge	X					

A. Electrically Responsive soft actuators

Soft, flexible materials able to convert one form of energy to other form of energy are plentiful, and include polymers, gels, fluids, paper, and even stand-alone CNTs. The first technique is to use dielectric elastomeric actuators (DEAs) made of soft materials that actuate through electrostatic forces- an important development in the quest for artificial muscles [20, 21].

Furthermore, as these types of actuators are compatible with conventional electronics, it is easy to integrate them with electrical drivers and power sources. The applications are endless; some of the biggest research potentials are seen in artificial muscles [23–26], small-scale robots [27–29], manipulation of microscale objects [30, 31], and microfluidic systems [32, 33].

One of the biggest challenges in soft robotics is designing flexible actuation systems capable of high forces, to replicate the functionality of muscles in the animal body.

DEA technique has some limitations. First most designs that use DEAs require a rigid frame that prestrains the elastomer

[22]. Apart from this technique requires high voltages, which is undesirable for many applications.

B. Magnetically Responsive Soft Actuators

Soft composites with magnetic fillers can be actuated in an external magnetic field. Typically this involves incorporation of magnetic particles into a soft compound, creating an effective magnetization profile which varies in both the magnetization direction and magnitude [34–38].

When these actuators are subjected to an external magnetic field, the embedded magnetic particles try to align with the magnetic fields, generating deformation, torques, contraction, elongation, and bending.

As magnetic fields can penetrate through a wide range of materials, these magnetic actuators are ideal candidates for targeted drug delivery, microsurgery, microfluidics, and assembly within the body [39–44].

Although their application for microactuation purposes has been limited, the prospects of remote control and large displacements renders them useful, and even unavoidable in certain circumstances. The fact that poor electromagnetic flux in micro domain happens to be the most stringent limitation.

C. Thermally Responsive Soft Actuators

Thermal actuators based on material expansion are widely used in traditional MEMS systems, partially due to the ease of Joule heating. Depending upon the material's coefficient of thermal expansion, heat will cause a volumetric change, inducing actuation.

Thermally triggered actuators include those activated by infrared (IR) or near-infrared (NIR) light, thermal radiation, or Joule heating. Joule heating, also known as resistive heating, works by stimulating conductive materials electrothermally. Thermal actuators can be remotely powered and heat can be applied globally or locally, e.g., via lasers. Thermal triggers are typically safer and can be used around living cells, as long as the temperature remains between 4 and 37 °C [45]. However, actuators that are triggered by heat tend to be considerably less efficient and slower than their counterparts.

D. Pressure-Driven Soft Actuators

Pressure-driven soft actuators fall under a category of structures known as compliant mechanisms. A wide range of compliant mechanisms exist, the studies pertaining to high-precision machines and microelectromechanical systems (MEMs) have been discussed and reviewed [46]. Here we focus primarily on relatively new pressure-driven soft actuators that are employed for soft robotic applications.

Although it is less popular than thermally and electrically driven nano and microscale electromechanical systems [47]. These soft actuators can produce admirable force, even at small scales. Reviews of miniature pneumatic and hydraulic actuators include the works of De Volder et al. [48] and Greef et al. [49]

E. Photoresponsive Soft Actuators

Light-induced soft actuation is compelling because it can be remotely and accurately controlled and rapidly modulated [50, 51]. Photochromic molecules play a major role in synthetic photoresponsive systems, capturing optical signals and translating these singles to useful property changes such as stress and strain [52]. These molecules have found their use in microscale soft and flexible actuators composed of polymers, gels, fluids, and even photostrictive materials. Near-infrared (NIR) light stimulated soft actuators with wide application prospects in tissue engineering [53], biomedical devices [54], and robotic technology [55, 56]. However, the real application of NIR-responsive soft actuators was plagued by two key limitations: moderate photoactuation speeds and poor mechanical properties [57-60].

F. Chemically Responsive Soft Actuators

Chemically responsive actuators can encompass a variety of mechanisms. Actuators that can move upon application of a chemical, typically involving some chemical reaction, induced stress, or deformation. The transformation of chemical energy into mechanical energy is called chemomechanical motion.

A soft material such as polymers and gels have the ability to selectively diffuse chemicals, causes mechanical stress in the material and allows a variety of chemical reactions to occur internally [61].

However, in general, these types of actuators tend to be highly sensitive, response times are variable and depend upon the diffusion rate into the materials [61]. Even in some case, actuation rates can be on the order of minutes or hours. The rate of diffusion can be increased by either increasing the actuator's porosity [62] or by employing surface treatments [63]. Chemically responsive SMPs have gained traction, especially toward the field of medical applications [64, 65].

G. Water-Responsive Soft Actuators

Researchers have demonstrated water-responsive artificial actuator systems using SMPs, LCPs, hydrogels, and paper, and have shown applications from simple benders to grippers, walkers and artificial muscles.

Owing to change in humidity, sensivity of hydrogels varies so has obvious example in actuators [66]. Sidorenko et al. demonstrated a fast humidity-driven reversible actuation of complex micropatterns in hydrogel nanostructures [67]. These hydrogels shows changes in shape, as their temperature is raised above a threshold value known as the lower critical solution temperature. The water gradient-driven inchworm was able to generate contractile stress up to 27 MPa, lift objects 380 times its own weight with second-to minute-long response times [68].

Much work is directed ahead of the creation of water responsive materials that are completely biodegradable and biocompatible. In a recent example, Wu et al. developed biocompatible and biodegradable SMPs from cellulose nanocrystal composites for eventual use in minimally invasive surgery [69].

H. pH-Responsive Soft Actuators

Researchers have proposed a range of actuators that experience swelling or shrinking depending on the level of pH in the surrounding fluid [70]. These types of actuators

are considered to be especially useful for medical applications inside the body, where other stimuli such as heating and light, can be hard to apply [71].

Materials that can be made pH-responsive include organic polymers, hydrogels, LCEs, and SMPs. Hydrogels have been explored for their use as pH-responsive biocompatible cantilevers [72], microgrippers [73], smart microcapsules [73], microscale lenses [74] and valves for microfluidic systems [75].

LCE films demostrated by Haan et al. were capable of a nanoscale twisting motion when subjected to IR heating or changes in pH between 2.3 and 6.1 [76]. pH-responsive actuators in general, however, tend to be especially slow, and work is in progress to improve the response times from the scale of hours to minutes [77–79].

I. Surface-Tension-Based Actuation

A surface tension driven actuators are shown attractive opportunity for its usage in microfluidics [80], accurate micropart assembly [81] which has been potential down to the nanoscale [82-84].

Fargette et al. showed capillary-force triggering of snap-thorough instabilities in elastic beams, with the resulting motion occurring in milliseconds [85]. With liquid droplets at speed, dynamic capillary folding can also be accomplished. The folding is dependent on both surface tension forces and inertia [86].

One particular limitation that exists in the interaction of flexible surfaces and droplets is the tendency for all surfaces to wrap around the liquid. Geraldi et al. recently explored the interaction of flexible super hydrophobic surfaces and liquid droplets, which were able to prevent this type of behavior [87].

III. Soft Materials

Here, we define soft actuator materials as highly deformable materials or composites that can be activated by external stimuli to generate desired forces/torques and motions. Soft materials adapt themselves to highly flexible and deformable structures, providing additional functional advantages, such as enabling entrance into small apertures, grasping of delicate objects. To facilitate easy deformation, depending on their geometrical configurations, many of these actuators are constructed either from materials that have low elastic moduli or those that incorporate fluids.

The following sections give a brief introduction to the major categories of soft, stimuli-responsive materials, along with their characteristics and composition.

A. Polymers and Gels

Here, we will discuss a range of soft actuators that are constructed by polymers and gels. We will also discuss a range of actuators that are created by gels, e.g., hydrogels, aerogels and oil-based gels. These actuators can use extremely diverse stimuli for actuation.

There are various classes of polymeric materials that are widely used and designed to respond to many different stimuli.

a) Electrically Responsive Polymers:

Electroactive polymers (EAPs) are polymers that can change shape and size upon electrical stimulation including: i) nonionic EAPs driven by electric fields or Coulomb forces, such as dielectric elastomers, ferroelectric polymers, electrostrictive polymers, and LCEs, and ii) ionic EAPs driven by mobility and diffusion of ions and their conjugated substances such as ionic conducting polymers and ionic polymer–metal composites (IPMCs).

Liquid-crystal molecules, also called mesogens, are typically polar, relatively stiff rod like molecules that can be easily reoriented in electric fields. Liquid-crystal elastomers (LCEs), and liquid-crystal polymer networks (LCNs), depicted in **Figure 3**. [89] LCEs and LCNs are most widely studied for use in actuators due to their material properties.

The organizations of the mesogens in these materials define the material's phase, with two important examples being nematic and smectic. In the nematic phase, the mean orientation of the mesogens is uniform and in the smectic phase, the meogens are organized additionally, in separate layers [90]. When nematic-phase LC materials are heated, they can transition to an isotropic phase, where the mesogens are randomly aligned and bundled, and producing reversible and repeatable contraction, as depicted in **Figure 3** [89].

Under an electric field, LC mesogens will attempt to align themselves along the field lines. As they are attached to polymeric chains, this results in an overall deformation of the material.

Actuation without an isotropic phase transition is also possible, such as the case of smectic ferroelectric LCE films actuated by electric fields [91].

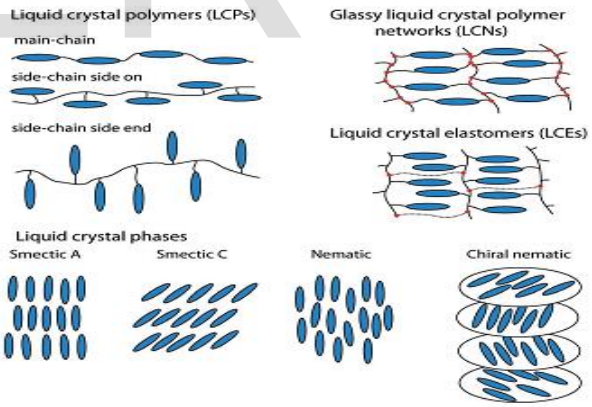

Figure 2. *Liquid-crystal polymeric materials and LCE phase transition between nematic and a disordered, isotropic phase.*

b) Ferroelectric Polymers:

Ferroelectric polymers are a class of crystalline polymers that are able to transition from polar to nonpolar states, producing lattice strain and dimensional change under electric fields [92].

Ferroelectric polymers are easily produced, cheap, and lightweight, and can be cast into any shape however one of the biggest challenges related to ferroelectric actuators and

non-ionic polymers in general, is how to significantly reduce the applied field required to drive the high strain and improve the elastic energy density [93].
The most popular choice of material for these actuators has been the piezoelectric material poly (vinylidene fluoride) (PVDF), commonly used in acoustic transducers. The same dipolar structure that enables piezoelectricity also causes pyroelectricity, i.e., the electrical response to a change in temperature [94].

c) Ionic Conducting Polymers:

Although polymers are commonly known for their excellent insulating properties, conjugated polymers can become highly electrically conductive when subjected to a structural process called "doping" [96]. The doping process detaches or adds electrons to the polymer backbone resulting in cations and anions that can move freely under the influence of electrical fields thus increasing conductivity [97]. These conducting polymers can exhibit large dimensional changes depending on their oxidation state, thereby converting electrical energy into mechanical work. The switching of a conducting polymer between the oxidized and the reduced states is a reversible process that can be driven electrochemically by small changes in voltage [98].
Conductive conjugated-polymer actuators feature low operation voltages and are typically lightweight, flexible, and biocompatible. Compared to ferroelectric polymers, these actuators are capable of generating an order of magnitude more stress. Polypyrrole and polyaniline are two of the most investigated conjugated polymers because of their good chemical stability and substantial strains [99].
IPMCs are also known as ionic polymer–conductor composites, ionic conducting polymer gel films, and ionic polymer transducers. The classic IPMC actuator layout includes an ion-conducting polyelectrolyte membrane with thin flexible electrodes on both sides, which allows the application of electric fields along the membrane (Figure 3). Upon the application of an electric field, the positively charged ions tend to accumulate near the cathode, which, in turn, exerts stress on the surrounding molecules due to the high concentration. This highly localized stress results in bending of the IPMC structure [100].

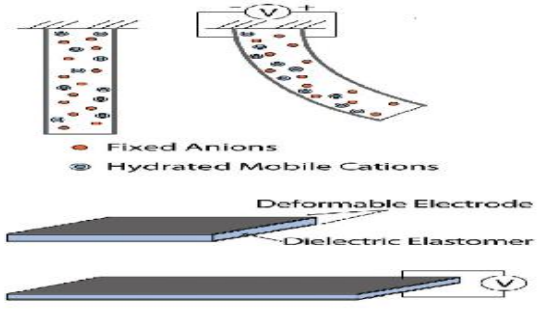

Figure 3 .*Ionic and dielectric elastomer actuators*

IPMCs have been used for a multitude of robotic applications. Because of their ability to function in aqueous solutions, underwater fish, [101] ray, [102] jellyfish, [103] walking, [104] and catheter robots [108] have been extensively explored.
Despite all of their advantages, IPMCs suffer from several significant drawbacks including low actuation bandwidth, relatively low durability in dry operation, environmental unfriendliness, and high costs [105].

d) Electrically Responsive Gels:

Of all the solid-state materials, gels provide the biggest actuated change in volume;[106] In this section we will discuss the EAP gels, capable of absorbing and releasing large amounts of fluid under electric fields [107] .
By applying an electric field to a submerged ionic solution, will cause it to swell asymmetrically toward the cathode. It is because of mobile-ion concentrations difference between the inside and outside of the gel [108].
Ionic EAP gels require low driving voltages, use soft biocompatible materials, and promise many future applications, including manipulation of biological components in aqueous solutions, soft actuators, cell scaffolds and replacement of biological tissues [109]. The drawbacks of polyelectrolyte gels are that their electromechanical response is typically slow, inevitable heat and gas generation with electrolysis of the aqueous solution [110], and large leakage currents under strong electric fields and strongly dependent on both temperature and humidity [111].
Several types of small-scale ionic-gel-based robotic actuators exist. Osada et al. showed worm-like motion in one of the first robotic demonstrations of ionic gels [112]. .
Driven by shortcomings in ionic EAP gels, researchers have recently started looking into soft materials made of plasticized PVC gel (Figure 4)

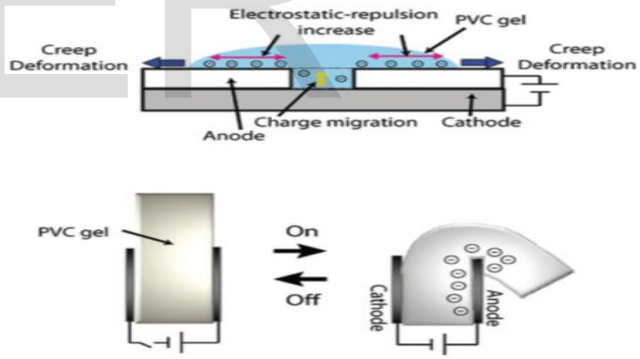

Figure 4. *Various electrode arrangements for actuation of PVC gel, a type of non-ionic electric-field-responsive gel.*

PVC actuators consist of PVC gel sandwiched between conductive meshed or solid electrodes.
The force generated when under an applied electric field stems from a creeping motion along the anode. Several groups are researcher working on artificial muscles by stacking of PVC gel actuators [113].

e) Magnetically Responsive Polymers and Gels:

There are generally two types of polymer-based magnetically responsive soft actuators. The first has a continuous magnetization profile and the second involves

creating a discrete magnetization profile, where only specific parts of the actuator will respond to an applied field.

A large variety of magnetic soft materials and ferrofluids have also been used, including a variety of paramagnetic, superparamagnetic and ferromagnetic particles with length scales of nanometers to micrometers [114,115]. Magnetic particles have been incorporated into soft polymers and gels in various ways. The most widely used approach is to simply mix the magnatic particles into uncured material and encase them upon curing. Once the particles have been embedded, if they have hard magnetic properties, the material can be magnetized by a large applied magnetic field. A typical process results in an actuator that has a continuous uniform magnetization, where each part of the actuator is magnetized at the same magnitude and in the same direction.

Zrinyi et al. has shown that it is possible to use the spatial gradients of the actuating fields to elongate the length of a uniformly magnetized gel [115].

Non-uniform continuous magnetization profiles were first introduced by Kim et al. [115]. An external magnetic field was used to control the orientation of the magnetic particles in an uncured solution; next, UV light was used to polymerize areas in sequence to enable varying particle orientations along the material. This fabrication method was simple, however, requires a curing method that is spatially controllable, limiting the possible range of materials. An alternative approach was proposed by Diller et al [116]. Here, the polymer was cured and then spatially deformed before magnetizing the embedded particles. The result was a soft actuator capable of propulsion, steering, and control in small groups [117].

Discrete magnetization profiles can be fabricated by simply attaching permanent magnets to polymers and gels [118], or by folding a material around them [119]. With two attached permanent magnets, Crivaro et al. and Yim et al. created compliant bistable mechanisms that can be used for swimming [118] and drug delivery [120].

f) Thermally Responsive Polymer and Gels:

Hygromorphic materials expand or contract when in contact with water or with changes in humidity. With certain polymers and gels, this water swelling is controllable with changes in temperature. One of the most widely used materials is poly (N-isopropylacrylamide) (PNIPAM), which is suited for operation at room temperature and near living cells [121].

In 2009, Okuzaki et al. proposed a new class of EAPs based on the electrical conductivity and hygroscopic nature of conductive polymers [122] .These polymeric films, composed of polypyrrole, exhibit significant volume expansion in air, when an electric current is passed through them as a result of Joule heating.

Recently, Taccola et al. achieved bending through the use of a bilayer system composed of a humidity-responsive material backed by an inert material (Figure 5) [122]. Further improvement with a combination of a stimuli-responsive hydrogel and fiber-like macroscopic graphene materials [123].

When exposed to a stimulus, typically heat, liquid-crystal materials can undergo phase transitions between a liquid-crystalline phase to an amorphous, isotropic phase. More generally, this corresponds to an ordered and a disordered mesogen arrangement.

With good initial mesogen alignment, the phase transition can result in very large strain in this direction, as shown in Wermter et al. where >300% was achieved [124].

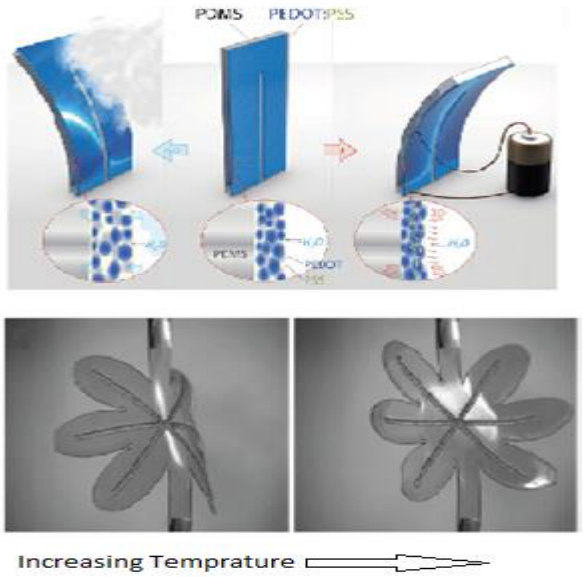

Figure 5. *Thermally responsive hygromorphic actuators*

Ahn et al. used inhomogeneous and anisotropic material stretching to pattern the mesogen orientation; [127] others have demonstrated alignment using polarized light and photomasks, producing patterned, structured films [125]. By using exchangeable covalent links whose topology can change with a change in temperature, LCEs can be heated, their mesogens realigned as desired, and then be actuated into a new shape [128]. With the incorporation of CNTs, this process can be accomplished photothermally, where both repeated crosslinking and actuation are achieved with IR irradiation [126].

Shape-memory polymers (SMPs) are materials that are able to "remember" one or more shapes. A deformed temporary shape can be fixed under certain conditions, commonly polymer crystallization and then recovered under various stimuli including heat, light, and solvent [129].

Heat remains one of the most common stimuli used with SMPs, and includes SMP electrothermal, photothermal and inductive heating with magnetic fields. Conductive fillers, such as CNTs, carbon black, polypyrrole, and nickel powders, serve not only to increase electrical and thermal conductivity, but can also improve SMP mechanical strength and recovery stress [130–136]. Efforts to improve SMP properties have led to materials that can be strained up to 1000% before failure, with recovery up to 400% strain [137]. Work by Voit et al. has pushed this even further, with fully recoverable strains of over 800%, with a near-room-temperature glass transition of 28 °C [138]. Liu et al. was able to achieve large bending and folding with local light

absorption to assemble various shapes and enclosures [139]. Using the ability to thermally tune the SMP stiffness, the motion of miniature flexure linkages can also be controlled [140] and be used to create effective bi-stable states in dielectric elastomer actuators [141].

g) Photoresponsive Polymers and gels:

Light-responsive polymers are able to reversibly change their chemical and/or physical properties, including their shape, surface wettability, membrane potential and permeability, solubility, fluorescence, and transition and phase-separation temperatures upon light irradiation [141,144]. Induced deformations of polymers include bending, contraction, and swelling motions. These deformations are typically reversible either by applying and removing heat, by changing the wavelength of the light source, or by removing the light altoghether.

The actuator response depends on various factors, including external factors such as the wavelength and intensity of the light and the irradiation time [143].

The two biggest classes of synthetic light-responsive polymers include liquid-crystal polymeric materials and SMPs. although most photoinduced actuation occurs by UV irradiation, there have been a few examples using NIR light on biological materials in aqueous solutions for intravenous drug delivery applications [145].

The basic mechanism of operation is depicted in Figure 6. As with thermally responsive liquid-crystal polymeric materials, mesogen alignment has been used to create photoresponsive actuators with greater motion complexity and stroke length [146,148,149].

Recent work by Zeng et al. shows the fastest response time of an LCE to date, at 1.8 kHz.[150] Future work includes targeting direct utilization of sunlight instead of high-power UV irradiation,[147] or use of other materials like diarylethene chromophores instead of azobenzenes for faster actuation speeds.

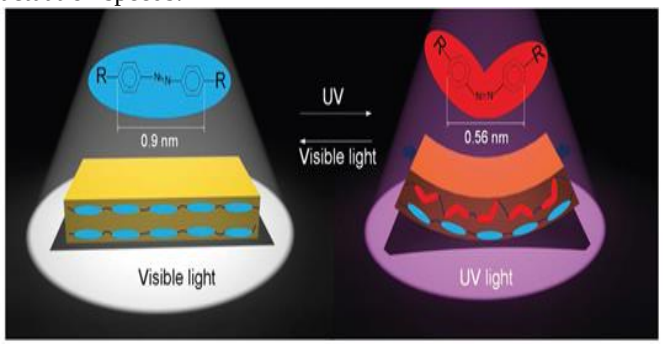

Figure 6. *LC photoresponsive actuators based on azobenzene photoisomerization*

Photoresponsive SMPs are first stretched by an external force, and then exposed to UV light to fix the elongated shape. After the external stress is released the film can stay in the elongated state for an extended period of time. Upon irradiation with a different wavelength, the original shape can be recovered [152].

Photoresponsive gels typically show a combination of sensitivities to light, temperature, and pH values [151]. Under every light condition, increased temperature typically causes a volume contraction; likewise, increased pH values typically diminish the swelling capability of the gel [23].

B. Fluids

Here, we will discuss principles behind and examples of fluid based soft actuators. In general, these actuators can be activated by modification of viscosity, an increase of pressure and/or selective surface-tension control of the liquid interface.

In general, fluids have a number of disadvantages compared to solid-material actuators. For example, fluid-based actuators may not be repeatable as they can be subject to leakage.

Furthermore, many fluids are also highly dependent on environmental conditions and in small quantities can easily and quickly evaporate. However, These shortcoming can be addressed by encapsulating the fluid in elastic chambers, films, or gels.

a) Electrically Responsive Fluids:

Electrorheological (ER) Fluids are a class of liquids with rheological properties which could be tuned under an applied electric field. When an electric field is applied, the difference between the dielectric constant of the liquid and it's particles leads to polarization and the formation of a dipole moment. The result is particle accumulation in chains along the direction of field and a subsequent increase in fluid viscosity [153]. The transformation is fast (order of milliseconds) and the change in viscosity is quite significant, especially in the case of giant ER fluids (GERFs) [154].

ER fluids can be formed out of a variety of particles and carrying fluids [155–157]. However, these suspensions do have a tendency for particle solidification that can cause clogging or damage when used in microchannels.

Smart GERF droplets, alternatively, have interesting potentials for microscale manipulation in microfluidic systems. GERF droplets are capable of creating pressure differentials and also can be used for sorting (Figure 7) [153].

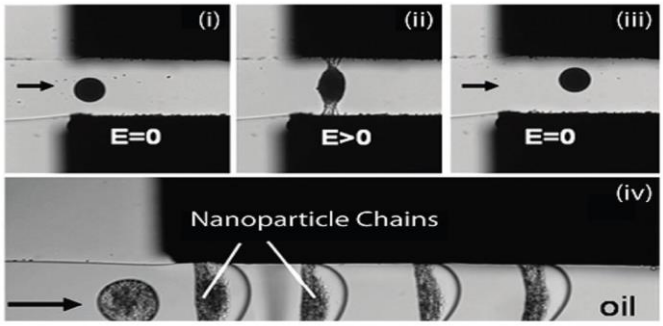

Figure 7. ERF droplet in immiscible liquid stopping under an applied field

b) Magnetically Responsive Fluids:

Magnetorheological fluids (MRFs) and ferrofluids are both liquid suspensions of magnetic particles. They differ

primarily in their particle size, where MRFs of one to tens of micrometers and ferrofluids commonly contain particles with diameters from 5 to 20 nm [159,160]. When MRFs are exposed to a magnetic field, the magnetic particles within the fluid will form a gel of dipoles, aligning and forming columns along the direction of the field [158]. This causes a significant increase in viscosity and an effective transformation from liquid to solid like behavior. Recent work has replaced magnetic particles with nanoscale wires to improve the yield stress at lower magnetic fields [161]. Liquid marbles can also be made responsive to magnetic fields, and are usually modified in one of two ways: by using hydrophobic or superhydrophobic magnetic nano- or microparticle coatings [162,163].

Similar to the capillary origami controlled by an electric field, magnetic capillary origami has been demonstrated with the use of a film suspended in a ferrofluid [164].

c) Pressure-Driven Elastic Fluids:

Historically, the most frequently used microfluidic actuators are membrane actuators. Membrane actuators are systems composed of clamped, planar elastic sheets that are pressurized and expanded. This concept has later been extended to pumps and valves for microfluidic systems and lab-on-a-chip purposes [165–170], as well as microoptics [171], tactile/ Braille displays [172], and grippers [173].

One of the most used materials for small-scale elastic fluidic actuators is PDMS. This is typically cast and bonded to create an internal void. Konishi et al. had demonstrated bending motion of a gripper for safe handling of delicate objects including fish eggs, cells, and hair [174-176]. It was relatively uncommon to generate compact twisting motion in elastic fluidic actuators until recently.

Pressure-driven linear actuators have been demonstrated using several main concepts. The first is microbellow actuators with symmetric corrugation, which extend upon pressurization [177,178]. Contraction can be achieved, as in McKibben style actuators, where stiff fibers are added to the elastomer along the length of the cylindrical chamber. As the fibers inhibit further extension, upon pressurization, the chamber instead expands laterally resulting in a decrease in the overall actuator length [179].

d) Thermally Responsive Fluids:

With a uniformly heated and structured surface, Linke et al. has demonstrated Leidenfrost droplet speeds as high as 5 cm s−1[180]. A Leidenfrost droplet forms when a droplet is placed on a hot surface; the liquid boils and forms a vapor layer between the substrate and liquid, effectively levitating the droplet. With a ratchet-shaped surface, this vapor production can be used to propel the droplet forward [180]. While liquid metal can be directly actuated electrochemically Or through electrowetting [181,182], it also allows heat-based stiffness change [183–185].

e) Photoresponsive Fluids:

As with gels, most applications related to light-induced motion in fluids exist through photothermal effects. Using asymmetrical irradiation of blue and UV light, Ichimura et al. has demonstrated the motion of an olive-oil droplet on a flat surface coated with a monolayer of azobenzene [186]. By shining light on the surface, azobenzenes are isomerized, creating the surface free energy gradient. The cause the droplet to first undergoes a decrease in diameter and then increasing the contact angles of both the receding and advancing edges. Eventually, the droplet starts moving at speeds ≈35 μm s-1. Recently, researchers demonstrated the first photochemically induced actuation of a liquid-metal marble, composed of an alloy of gallium, tin and indium with a coating of nanoparticles made from WO3 [187].

C. Paper and carbon

Paper has a long history of use in printing, cleaning and packing, it is only relatively recently that it has formed the basis of actuators as a new smart material. Paper is composed of a porous network of cellulose fibers [188], is typically biodegradable, cheap, abundant, and lightweight, and it has great potential applications [189-191].

Despite the high Young's moduli of carbon nanotubes (CNTs) (>1000 GPa when axially loaded [114], they, along with carbon particles and graphene, have been frequently used in number of potential applications.

A comprehensive review of CNT sensors and actuators was published in 2008 by Li et al [192].

a) Electrically Responsive Paper and carbon:

The piezoelectric properties of cellulose have been known for some time, however, from the last decade it was functionalized [193,194]. The first paper actuators, termed electroactive papers were composed of metal-coated (aluminum, silver, gold) paper cantilevers 30 mm long, able to displace the tip 4.2 mm with a force of 12.7 mN at 0.23 V m−1 and 7 Hz [194–196]. The mechanism of cellulose actuation is attributed to a combination of piezoelectric effects and ion migration [196]. Efforts to increase performance include enhancing the ion-migration effect by coatings with conducting polymers and ionic liquids [197], and incorporating MWCNTs into the cellulose for an increase in mechanical strength and power output [198].

Several mechanisms for electrically actuating CNTs exist, including electrostatics [199].

The majority of related papers demonstrate translational displacements or cantilever bending, but CNT torsional actuators have also been shown [200]. Further work has been done examining the effect of different sources of CNTs with different electrolytes on the efficiency and work capacity [201].

b) Magnetically Responsive Paper:

Ding et al. has tested a variety of papers and their absorption of an oil-based ferrofluid, reporting the cantilever actuation and force production when subjected to a magnetic field [238].

Depending on the material used, various approach es demonstrated. Fragouli et al. demonstrated dry, waterproof magnetic cellulose sheets, which may prove to be an

attractive option for future magnetically responsive paper actuators [202].

c) Thermally Responsive Metals and carbon:

The shape-memory effect in metals, specifically the widely used nickel titanium (NiTi) shape-memory alloy (SMA), has become commonly used in soft robotic systems. Their flexibility allows them to be easily incorporated into soft systems, such as the meshworm presented by Seok et al. [203], as well miniature systems such as a miniature flea-inspired jumper. [204]. Significant SMA bending can also be achieved, with both grippers and freestanding crawlers demonstrated [204–208]. Light-absorbent and conductive carbon nanoparticles like CNTs, and graphene are incorporated in thermal actuators to improve its performance. Although the actuation of CNTs themselves can be accomplished through the application of heat with the thermoelectric effect [209], they are more frequently used in soft actuators as a composite component.

Recent work includes a bilayer swimming robot (7 mm x 1 mm) made of PDMS as substate and grapheme as filler, able to deflect its tail 1.5 mm due to uneven heating when an NIR laser was illuminated for 3.4 s [210]. Similarly, bilayers composed of PDMS and CNT bucky papers, as well as reduced graphene oxide (rGO), have also demonstrated large bending strains [211,212].

IV. Future Perspective

The largest driving force behind the field of soft small scale robotics is arguably biomedical applications for in-body diagnosis, treatment, and surgery, as well as precise manipulation of biological components such as embryos and cells [213,219].

Correspondingly soft materials open up new prospects for bioengineered and biohybrid devices [214]. While the possible stimuli and their associated actuation mechanisms may vary, many tend to be slow, which has led to additional effort to increase response times by modifying materials [215,216].

As soft actuators shrink, more and more researchers depend on remotely applied stimuli, leaving control and sensing off board while working toward more complex material programming for added embedded functionality.

Combining the self-sensing capabilities that exist in many of these materials has the potential to create soft robotic system that can truly sense, respond, and interact with their environment. Additionally, work toward mass manufacturing has the potential to enable inexpensive soft small-scale robotic system [217,218].

Significant advances have been made in developing biomaterials suitable for minimally invasive surgery (MIS) soft robots [219] and a tissue growth scaffold made from biopolymers. Soft robot could be designed with biomaterials that release therapeutic agents locally [220] or as deposit materials that the body can use as a scaffold for tissue repair [221].

Soft actuators built from biological materials and living cells would inherit the advantages of these materials: they have extraordinary potential for self and they can be powered by safe, energy-dense hydrocarbons such as lipids and sugars; and they are biocompatible and biodegradable, making them a potentially green technology.

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