Chapter 12

Simultaneous Smart Actuating-Sensing Devices Based on Conducting Polymers

José G. Martínez, Joaquín Arias-Pardilla and Toribio F. Otero

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/51733

1. Introduction

Towards the end of 1970s new artificial organic materials, conducting polymers (CP), were discovered (Chiang et al., 1977; Inzelt, 2011; Shirakawa et al., 1977). Since then, most of the scientists working on CP became interested by the fact that their conductivity can shift, in a reversible way, over several orders of magnitude by oxidation/reduction (also called doping/dedoping) processes. The availability of these new organic semiconductors has opened up possibilities to rebuilt electronics and microelectronics producing flexible devices (Guo et al., 2010; Klauk, 2006; Perepichka & Perepichka, 2009; So, 2010).

Besides conductivity other properties such as stored charge, stored chemicals, volume, porosity or colour also change during doping/dedoping, under electrochemical control, in parallel with the material composition (counterion content) along the redox reactions (Otero, 2008). Any intermediate oxidation state determines a chemical equilibrium characterized by an equilibrium potential. Any physical (temperature, pressure, applied current) or chemical (electrolyte concentration) magnitude affecting the chemical equilibrium modifies the electrical potential of the material that therefore can be used as a sensor of that magnitude (Otero, 2009).

These properties, whose value changes with the material composition, are allowing the development of different devices (Onoda et al., 1999a; Otero et al., 1992a; Otero et al., 1992c; Pei & Inganäs, 1992a). Volume variations driven by oxidation/reduction reactions are being used to generate new electrical motors having different configurations of the polymeric actuators (Alici et al., 2007; Smela et al., 1993; Wu et al., 2005).

We will present devices constructed with conducting polymers based on an electrochemical reaction and working, simultaneously, as an actuator and as several sensors of the surrounding conditions. During the movement they store and release charge working as a battery: they are multifunctional devices.

2. Electrochemical reactions in conducting polymers

Once generated (chemical or electrochemically), conducting polymers can be considered as both, classical unreactive materials having either a constant composition and a constant value of the magnitude of its physical and chemical properties; or new reactive materials varying their composition (polymeric chains, ions and solvent in different ratios) and properties along several orders of magnitude in a reversible way under electrochemical reaction (Otero, 1999), or promoted by redox agents present in solution (Kuttel et al., 2009).

2.1. p-doping

When the polymer chains are oxidized, consecutive electrons are removed from each chain generating an excess of positive charges (holes) along the chains. This excess of positive charges (lack of electrons) promotes the repulsion between the polymeric chains and the generation of free volume between them. This free space is occupied by anions arriving from the solution to compensate the emerging positive charges (keeping the electroneutrality) and solvent molecules to keep osmotic pressure balance (Huang et al., 1986; Otero, 1999; Tsai et al., 1988).

When the polymer is generated in the presence of small anions, they can be exchanged by other small anions present in solution by electrochemical reactions so a prevailing exchange of anion occurs during reaction:

$$\left(Pol^{0}\right)_{s} + n\left(A^{-}\right)_{sol} + m\left(Solv\right) \rightleftarrows \left[\left(Pol^{n+}\right)_{s}\left(A^{-}\right)_{n}\left(Solv\right)_{m}\right]_{gel} + n\left(e^{-}\right)_{metal} \quad (1)$$

where the different subscripts mean: *s*, solid; *sol*, in solution; *gel* indicates that the material is a gel formed by oxidized polymeric chains (Pol^{n+}) generated after the extraction of *n* electrons (e^{-}) through the metal (indicated by subscript *metal*) from neutral polymer chains (Pol^{0}), *n* anions (A^{-}) coming from the solution to keep the gel electroneutrality and m molecules of solvent (*Solv*) required to keep osmotic pressure balance.

When the polymer is generated in the presence of a macroanion, due to its volume and the interaction with polymer chains, this macroanion cannot be exchanged by the electrochemical reaction keeping trapped inside the polymer film. So, in order to keep the electroneutrality, smaller cations are exchanged with the solution during the reaction:

$$\left[\left(Pol^{0}\right)\left(MA^{-}\right)_{n}\left(C^{+}\right)_{n}\left(Solv\right)_{m}\right]_{gel} \rightleftarrows \left[\left(Pol^{n+}\right)\left(MA^{-}\right)_{n}\right]_{gel} + n\left(C^{+}\right)_{sol} + m\left(Solv\right) + n\left(e^{-}\right)_{metal} \quad (2)$$

where MA^{-} is the macroanion trapped inside the polymer film and C^{+} are cations exchanged in order to keep the electroneutrality.

Usually, the real redox process is not as easy as expressed by reactions (1) and (2): anions and cations are exchanged simultaneously (Hillman et al., 1989; Inzelt, 2008). Usually one of the previous interchanges prevails supporting the greater percentage of charge balance (Kim et al., 2010; Lyutov et al., 2011; Orata & Buttry, 1987; Torresi & Maranhao, 1999).

2.2. n-doping

Some CP such as PEDOT (Ahonen et al., 2000), polythiophene (Arbizzani et al., 1995) or polyfluorenes (Ranger & Leclerc, 1998) have an electronic affinity high enough to allow transitions from the neutral state to a reduced state, storing negative charges (by electron injection) on the chains at high cathodic potentials. In this case, very stable solvents and salts are required, as electrolytes, to perform this redox reaction:

$$\left(Pol^{0}\right)_{s} + n\left(C^{+}\right)_{sol} + m\left(Solv\right) + n\left(e^{-}\right)_{metal} \rightleftharpoons \left[\left(Pol^{n-}\right)_{s}\left(C^{+}\right)_{n}\left(Solv\right)_{m}\right]_{gel} \quad (3)$$

where Pol^{n-} represents the reduced polymer chains after insertion of n electrons. Here, in an analogous way compared to reaction (1), an excess of negatives charges promotes repulsion between polymeric chains generating the free volume that will be occupied by cations (exchanged with solution to keep electroneutrality) and solvent (exchanged with solution to keep pressure and osmotic balance).

2.3. Double doping

Some conducting polymers can be doped both, by p-doping and by n-doping. Thus, from their neutral state they can be reduced (suffering n-doping) or oxidized (suffering p-doping). In those polymers the energy difference between both processes is the electrochemical bandgap (Arias-Pardilla et al., 2010; Otero et al., 2011).

3. Reversible change of the electrochemical properties

Electrochemical reactions 1, 2 and 3 are reversible reactions moving through *n* consecutive oxidation states (Otero et al., 2012) having different content of the counterion. The value of the magnitude of those properties being a function of the material composition (electrochemical properties) can also be shifted in a reversible way under faradic control. As previously indicated, conducting polymers can be oxidized and/or reduced from their neutral state, with the entry/exit of ions and solvent. The most studied electrochemical properties of conducting polymers are: volume, colour, stored charge, stored chemicals, porosity or permselectivity, sensing responses or wetability, among others. The progressive and reversible variation of the value of these electrochemical properties allows the development of different devices and products. The change in volume will be reviewed in detail below: this is the most important property of conducting polymers for the development of actuators or artificial muscles.

3.1. Volume variations

A chain of conducting polymer in solution can be considered as an electrochemical molecular motor (Balzani et al., 2005; Davis, 1999; Otero, 2011): movements are produced by reversible conformational changes in chains originated by oxidation/reduction reactions.

The reversible conformational movement from a coil like structure to a rod like structure is produced by extraction (oxidation) or injection (reduction) of n electrons through n consecutive steps of one electron per step, together with movement of balancing counterions. This results in length variation of a free polymer chain in solution but, in polymer films three dimensional changes of volume are observed. The entanglement of the polymer chains in the film gives reversible swelling or shrinking changes of volume under reversible electrochemical stimulation (Fig. 1).

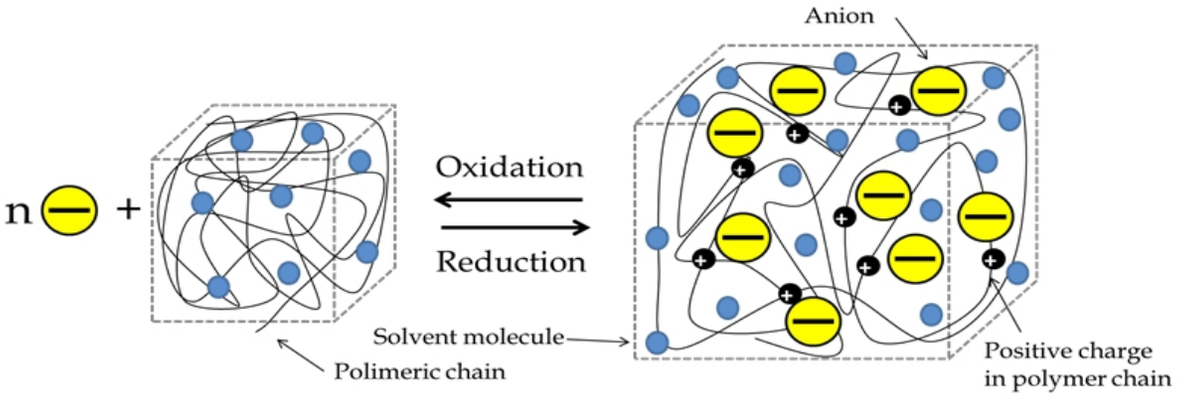

Figure 1. Schematic representation of the reversible volume change associated with the electrochemical reaction in conducting polymer chains during oxidation/reducction during p-doping exchanging anions.

Some mechanical test machines have been developed following length or thickness variations produced by submitting the film to different potential (Bay et al., 2003; Kiefer et al., 2007; Mazzoldi et al., 1998; Spinks et al., 2002) or current (Otero et al., 2006; Otero et al., 2007c) programs. In situ Atomic Force Microscopy (AFM) technique follows film thickness variation during reverse oxidation/reduction processes (Bieńkowski et al., 2011; Cho et al., 2011; Smela & Gadegaard, 2001). In this way, it has been possible to measure a volume difference between reduced and oxidized state up to 35% (Smela & Gadegaard, 1999). The volume change depends on multiple factors such as type of polymer, synthesis conditions (potential or current applied), electrolyte and solvents used.

4. Simultaneous sensing and actuating properties in conducting polymers

The driving reversible electrochemical reaction supports the development of simultaneous sensing and actuating properties by conducting polymer materials and by any electrochemical device based on those materials. The electrochemical working device (based on the electrochemical reaction) senses changes of any physical or chemical variable acting on the polymer reaction rate while working. This is the Le Chatelier principle applied outside equilibrium conditions (Smith, 2004). Therefore, for increasing values of the electrolyte concentrations or of the temperature working under flow of a constant current (constant reaction rate), lower values of the device potential are observed (the reaction is easier) during the transition between the same initial and final oxidation states of the materials. When a

greater mechanical work is required (moving faster, applying a higher current, or a higher mechanical stress is needed to move the actuator) the reaction gives increasing potential when the device moves between the same initial and final oxidation states.

Those sensing abilities are intrinsic properties of the reaction. They are characteristics of the material reaction and of any device based on this electrochemical reaction. So, the dual and simultaneous sensing-actuation property is expected to be quantified from electrochemical equations.

The evolution of the conducting polymer film potential with time E(t) during the movement from the same initial oxidation/reduction state to the same final oxidation/reduction state driven by flow of a constant anodic current is given by a stair function (Otero et al., 2012).

$$E(t) = \sum E_n(t)\,p_n(t) = E_1(t)\,p_1(t) + E_2(t)\,p_2(t) + \ldots + E_n(t)\,p_n(t) \tag{4}$$

where:

$$p_n(t) = u(t - t_n) - u(t - t_{n+1}) = \begin{cases} 1, t \in [t_n, t_{n+1}] \\ 0, t \notin [t_n, t_{n+1}] \end{cases} \tag{5}$$

Being t_n the time while the nth electron is removed from every polymeric chain and $E_n(t)$:

$$E_n(t) = E_0 + (n-1)\Delta E + \frac{RT}{(1-\alpha)F}\left\{\ln\left(\frac{i_a}{FV}\right) - d\ln\left[A^-\right] - e\ln\left(\left[Pol^*\right]_{initial} - \frac{i_a t}{FV}\right) - \ln k_{a0}\right\} \tag{6}$$

where E_0 is the standard potential, i_a is the applied current; n is the number of consecutive electrons extracted from a chain; ΔE is the increment observed in the potential when a new electron is extracted from a polymeric chain, R is the universal gas constant (R = 8.314 J K^{-1} mol^{-1}); α is the symmetry factor; F is the Faraday constant (F=96485 C mol^{-1}); V, the volume of the film; [A$^-$] the concentration of anions (counterion) in solution; t, the time of current flow; T is the experimental temperature; d and e are the reactions orders related with the concentration of anions in solution or to that of the active centres [Pol*] in the film (sites of the polymer where a positive charge will be stored after oxidation) and k_{a0} is the rate constant or rate coefficient for $E=E_0$.

Therefore, Eqs. 4 and 6 are the sensing equations: the evolution of the device potential during actuation is a function of either, driving (current) and working (temperature, electrolyte concentration and film volume) variables.

Being electrical machines, by integration of Eq. 6 the evolution of the electrical energy consumed by the electrochemical device (U_a) during the actuation time is attained:

$$U_a(t) = i_a \int E(t)\,dt = i_a t\left\{E_0 + (n-1)\Delta E\right\} + \frac{RTi_a t}{(1-\alpha)F}\left\{\ln\left(\frac{i_a}{FV}\right) - d\ln\left[A^-\right] - \ln k_{a0}\right\} + \frac{RTVe}{(1-\alpha)}\left\{\ln\left(\left[Pol^*\right]_{initial} - \frac{i_a t}{FV}\right) - 1\right\}\left\{\left[Pol^*\right] - \frac{i_a t}{FV}\right\} \tag{7}$$

The consumed energy (U_a) after any constant time (t) of current flow is also a sensing function of the same variables. Fig. 2 shows the good agreement between experimental and theoretical results for the consumption of three different charges (from the same initial oxidation/reduction state, three different final oxidation/reduction states are obtained) at different experimental temperatures by flow of a constant anodic current for three different times of current flow.

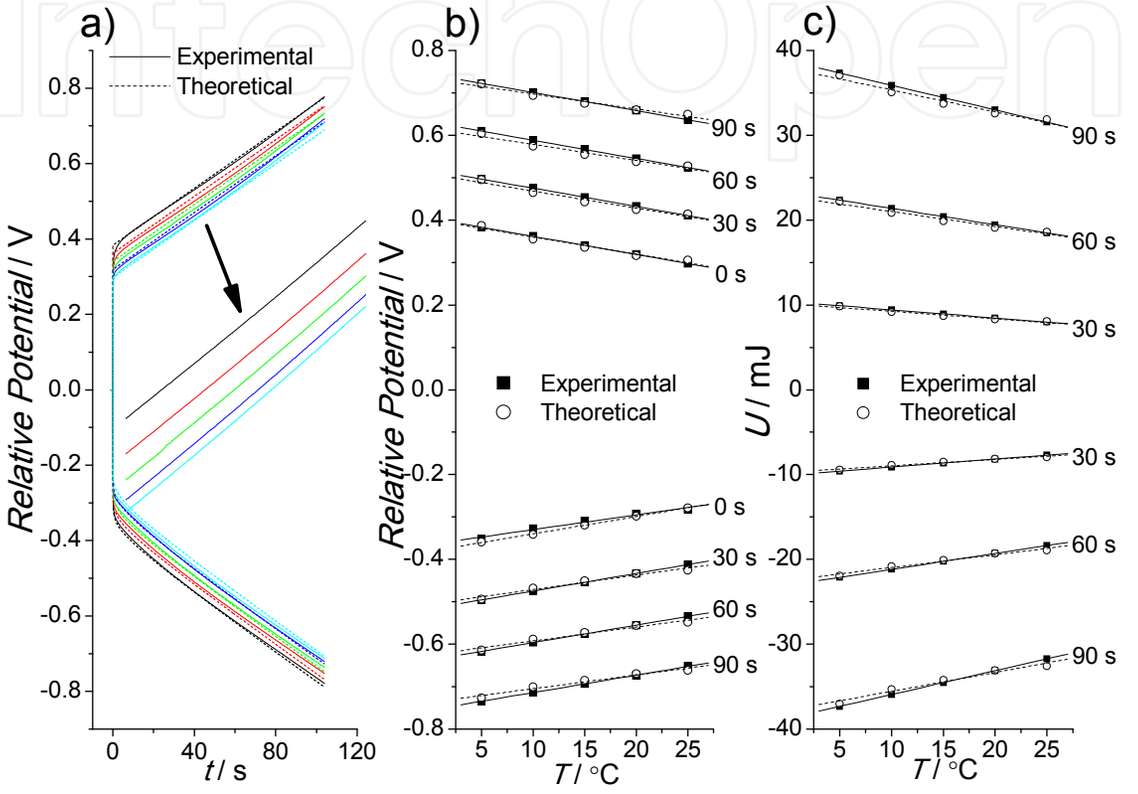

Figure 2. a) Anodic and cathodic experimental (full lines) and theoretical (dotted lines) chronopotentiograms obtained by flow of ±0.75 mA through a 1.6 mg pPy film (10.77 mm x 5.09 mm x 19 μm) at different temperatures (black line: 5ºC; red line: 10ºC; green line: 15ºC; blue line: 20ºC and cyan line: 25ºC) in 1 M $LiClO_4$ aqueous solution. b) Achieved potential after different times of anodic (positive) or cathodic (negative) current flow. c) Consumed electrical energy after the same times of current flow. Reproduced from (Otero et al., 2012), with permission of American Chemical Society).

5. Artificial muscles

In general, artificial muscles are devices attempting to reproduce composition, characteristics and capabilities of natural muscles. Different materials have been used as piezoelectrics (PZT), shape memory alloys (SMA) (Ouyang et al., 2008), carbon based materials as nanotubes (Baughman et al., 1999) or graphene (Huang et al., 2012) and polymeric gels. Also the pneumatic approach has been studied with contractile or extensional devices operated by pressurized air (Daerden & Lefeber, 2002).

Natural muscles transform chemical energy into mechanical energy and heat. Their actuation involves: a) aqueous media, b) an electric pulse arriving from the brain to the

muscle through the nervous system, c) liberation of calcium ions inside the sarcomere, d) chemical reactions (ATP hydrolysis), e) conformational changes along natural polymeric chains (actin and myosin) with change of the sarcomere volume and f) water exchange. Among of the above mentioned materials for artificial muscles, conducting polymers are the most similar to natural devices including: electric pulses, polymeric chains, chemical reactions, aqueous solutions (ions and water), volume variations, and strain and stress changes. Two families of electrical polymeric actuators can be differentiated (Otero et al., 2007a; Otero, 2000; Otero, 2007):

- **Electromechanical actuators**: the polymer responds to electric fields (E) and the polymer chains do not participate in chemical reactions (the structure of its intramolecular chemical bonds doesn't change) during actuation. In this type of actuator the dimension variations are proportional to E^2 for electrostrictive actuators and to E for electrostatic and electrokinetic (movement of ions and/or solvent molecules) actuators.
- **Electrochemomechanical actuators**: the polymer chains respond to electric currents and participate in electrochemical or chemical reactions, changing the structure of its chemical bonds, varying their composition and originating volume changes. In this case dimensional variations are under control of the electrochemical reaction becoming proportional to consumed charge. Conducting polymers can be used for the production of this kind of actuators. Whether carbon nanotubes and graphenes based actuators are electromechanical or electrochemomechanical is still under discussion (Gimenez et al., 2012; Mukai et al., 2011). Any electrochemically reactive material that can be laminated as stable films can be used as part of electrochemomechanical actuators.

From now on we will focus on electrochemomechanical actuators. These actuators have been built using different configurations as discussed below, always containing one or several films of conducting polymers, where reaction 1, 2 or 3 takes place. Volume variations generated by reactions 1, 2 or 3 are almost isotropic, while natural muscles are anisotropic devices. So to produce anisotropy, only volume changes following length variation of the films are used, with the consequent efficiency reduction.

5.1. Bending artificial muscles

Historically the first way to transduce reversible length variations in films of conducting polymers into macroscopic movements was through a bilayer, or bimorph structure, i.e. CP/passive layer (Otero et al., 1992b; Otero et al., 1992a; Otero et al., 1992c; Pei & Inganäs, 1992a) (Fig. 3). The variation of the mechanical stress gradient generated across the bilayer interface by swelling/shrinking processes induced by the electrochemical reactions in the conducting polymer film develops a macroscopic movement of the bilayer free end by the progressive bending of the device. The direction (clockwise or anticlockwise) of the movement depends on the prevalent ionic exchange (anions or cations) of the conducting polymer film. Conducting polymers with a prevalent exchange of anions swell by oxidation, pushing the bilayer free end meanwhile conducting polymers with prevalent cation

exchange shrink during oxidation, trailing the device. Different materials have been used as passive layer, for example a tape (Otero et al., 1992b; Otero et al., 1992a; Otero et al., 1992c; Pei & Inganäs, 1992a), a sputtered metal (Jager et al., 2000a; Jager et al., 2000b; Smela et al., 1993), a piece of paper (Deshpande et al., 2005b), a non conducting plastic (Higgins et al., 2003), a solid state electrolyte film (Alici et al., 2011; Baughman, 1996) or a thin film of any flexible material which is metal coated (i.e. by sputtering) (Deshpande et al., 2005a).

In a similar way it is possible to obtain bending movement from asymmetrical monolayers of the same conducting polymer, having an internal asymmetry capable of producing asymmetric swelling or shrinking across the film under the same electrochemical process (Okamoto et al., 2000; Onoda et al., 1999a; Onoda & Tada, 2004; Onoda et al., 1999b; Shakuda et al., 1993; Takashima et al., 2003; Takashima et al., 1997; Wang et al., 2002). Here half of the film has a prevalent anionic exchange, while the second half experiences a prevalent cationic exchange. These asymmetrical monolayers are obtained in two separate stages of electrogeneration using different salts and the same monomer. Other ways are being studied to produce asymmetric monolayers by physical means, for example, by growing the conducting polymer on adsorbed and porous materials (Li et al., 2004), or by electrochemical means generating a film of conducting polymer with a counterion concentration gradient (Okuzaki & Hattori, 2003; Sansiñena et al., 2003), conductivity (Nakano & Okamoto, 2001; Onoda et al., 2005) or morphology gradients (Han & Shi, 2006; Okamoto et al., 2001) by crosslinked networks.

All these bilayer devices require a counter-electrode in order to close the electrical circuit allowing the current flow. In this electrode (usually a metal) different electrochemical reactions as solvent oxidation, must occur during current flow consuming a major fraction of the electrical energy, resulting in pH variations and generating new chemicals, which can deteriorate progressively the bilayer device.

Trying to avoid the counter electrode and its associated problems, a three layer structure was proposed (Otero et al., 1992c). Initially, it was produced by using a central passive film (two sides tape) each side coated with a conducting polymer film (Fig. 3). The triple layer was immersed in an electrolyte allowing the current flow. One of the conducting polymer films acts as the anode while the second film acts as the cathode (Garcia-Cordova et al., 2011; John et al., 2008; Yao et al., 2008). But using this configuration it is also possible to obtain movement outside a liquid electrolyte media using an ionic conducting membrane to separate the two films of conducting polymers. This membrane can be obtained by solvent evaporation and UV irradiation (Blonsky & Meridian, 1997; Heuer et al., 2002; Sansinena et al., 1997; Song et al., 2002), or by formation of interpenetrated networks (Cho et al., 2007; Plesse et al., 2005; Vidal et al., 2009; Vidal et al., 2003). In this case, the two conducting polymer films are generated by chemical polymerization on the external part of the membrane. Using this approach, multilayer devices were constructed and characterized (Ikushima et al., 2009; Zainudeen et al., 2008). The three-layer configuration provides greater efficiencies of the consumed energy: the same current is used two times to produce opposite electrochemical reactions and volume variations in the conducting

polymer films; the anode swells and pushes the device and the cathode shrinks and trails the device.

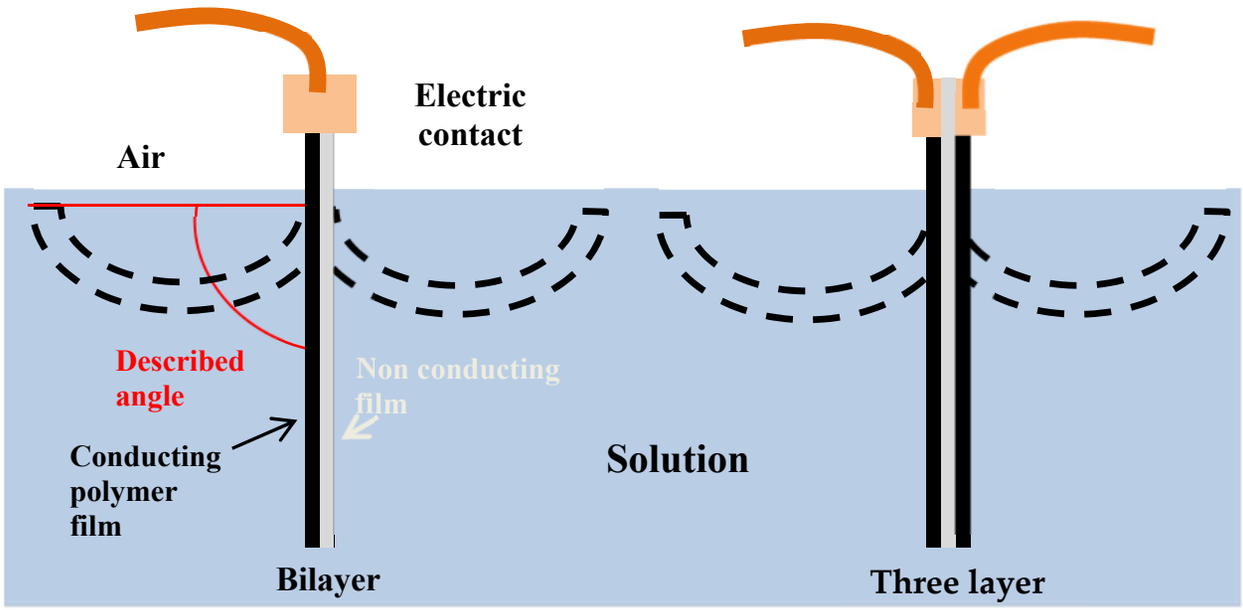

Figure 3. Bilayer and three layer devices in solution, formed by conducting polymer films and non-conductive films. Described angle is also shown.

5.2. Longitudinal or linear artificial muscles

Freestanding conducting polymer films are the simplest longitudinal actuators (DellaSanta et al., 1997). Its actuation principle is based on longitudinal expansion and contraction of the polymer during ionic exchange, although expansion and contraction occur in all three dimensions, as previously indicated. To improve the performance of these actuators overcoming problems of fragility, multilayered actuators were proposed (Hara et al., 2006; Kaneto et al., 2008; Kaneto et al., 2009), in which several thin conducting polymer films and an electrolyte (ionic liquid-soaked paper) are used to develop a compact and scalable longitudinal actuator with a high work output (Ikushima et al., 2009). Also folded films with Origami shapes provide good linear movements (Okuzaki, 2008).

Fibres of conducting polymer also can be considered as longitudinal actuators. Fibres can be obtained by extrusion (Mazzoldi et al., 1998) or by chemical polymerization over a fibre-shaped substrate (Ismail et al., 2011; Lu et al., 2002), or hollow fibre solid polymer electrolyte (Plesse et al., 2010) making it possible to obtain two concentric CP films separated by the electrolytic medium, allowing its movement in air (Dobbelin et al., 2010; Plesse et al., 2009; Vidal et al., 2010; Vidal et al., 2009). Microrods (Cho et al., 2011) or nanorods (Park et al., 2009; Vlad et al., 2012) of conducting polymers and bundles of films or fibres were investigated to produce vertical displacements of weights (Lu et al., 2002). Also, conducting polymer tubes were generated using springs and helical metallic wires (Ding et al., 2003; Hara et al., 2003; Hara et al., 2005; Spinks et al., 2003b) or zigzag metal wires (Hara et al.,

2004; Morita et al., 2010) as substrates, looking for uniform potential and current distribution. When individual fibres, bundles or tubes are used, a counter electrode is necessary, for the same reasons given above in the case of the bilayers.

Finally, it is possible to obtain linear displacement by combination of different bending structures as bilayers (Fuchiwaki et al., 2009; Naka et al., 2010; Otero & Broschart, 2006) or trilayers (Mutlu & Alici, 2010; Otero et al., 2007b) achieving longitudinal displacements over 60% of their original length.

6. Sensing and tactile muscles

As mentioned above, any reactive (electrochemical) device based on conducting polymers will sense every variable influencing the electrochemical reaction rate during actuation. Following this basic principle of the chemical kinetics sensing and tactile artificial muscles have been developed.

While a current is applied to the artificial muscle, producing a mechanical work, it is possible to follow the potential achieved in the muscle at every time. Under flow of a constant current (constant reaction rate) the achieved potential is lower when a variable which favours the electrochemical reaction increases. This is the case for temperature (Garcia-Cordova et al., 2011; Ismail et al., 2011; Otero & Cortes, 2003b; Valero Conzuelo et al., 2010; Valero et al., 2010) or electrolyte concentration (Arias-Pardilla et al., 2011; Garcia-Cordova et al., 2011; Otero & Cortes, 2003b; Otero et al., 2007b; Valero Conzuelo et al., 2010). On the other hand, the potential shifts to higher values when a variable makes the reaction harder: the muscle moves larger masses (Garcia-Cordova et al., 2011; Otero et al., 2007b; Valero Conzuelo et al., 2010) or moves the mass faster by applying now rising currents (Garcia-Cordova et al., 2011; Ismail et al., 2011; Valero et al., 2011).

Being the potential evolution a sensor of the working variables, the electrical energy (U) consumed by the device during actuation and obtained by integration is also sensor:

$$U(t) = \int E(t) I dt \tag{8}$$

Where t is the elapsed time, E(t) is the potential evolution during the actuation time and I is the constant applied current.

When a free muscle moves driven by a constant current finds an obstacle, the potential steps to higher values, trying to produce more energy and to shift the obstacle. The potential increment detects the object and its mechanical resistance to be shifted. Related with this property, artificial muscles with tactile sensitivity have been developed too (Otero & Cortes, 2003a).

7. Multi-devices: Actuators-sensors-battery-electrochromic

As mentioned above, different properties can be tuned simultaneously and in a reversible way during electrochemical reactions in conducting polymers. Electrochemical devices

created with conducting polymers may change several of those properties, such as volume, stored charge or color, at the same time. For example, using the same configuration, changing the quantity of conducting polymer used in the device, it's possible to obtain different optical or mechanical devices (Vidal et al., 2010).

Also, as the configuration of a three layer is the same of a battery with two conducting polymer films as electrodes, electrical charge is trapped in the actuator during electrochemical reaction. A way to recover that charge may be developed in order to recover that energy, acting now as a battery and moving the actuator in the opposite direction until a uniform oxidation state is attained in both polymer films (vertical position in Fig. 3).

8. Theoretical models

Several models have been proposed to characterize the electrochemomechanical behaviour of artificial muscles. At the moment, there exist different approaches from different fields as mathematics, physics or chemical-physics.

8.1. Faradic control of the movement

As mentioned above, artificial muscles are electrochemomechanical machines controlled by the electrochemical reaction occurring while actuating. As any electrochemical reaction, actuation in conducting polymers is controlled by the charge consumed during actuation. Volume changes are not an exception: according to reactions 1, 2 or 3, volume variations will be given by the number of extracted (or inserted) charges from (or to) the polymeric chains, promoting the swelling/shrinking and the ionic exchange during reaction.

For bending bilayer or trilayer artificial muscles, it has been experimentally proven that the described angle (α in rad) follows a linear relationship with the consumed charge (Q in C):

$$\alpha(t) = kQ(t) \tag{9}$$

where k is a constant (rad C^{-1}) depending on every actuator system: the device (conducting polymer and isolating tape) and the electrolyte where is moving.

By definition of the angular rate of the movement (ω):

$$\omega(t) = \frac{d\alpha(t)}{dt} = k\frac{dQ(t)}{dt} = kI(t) \tag{10}$$

This expression confirms the faradic control of the movement: the angular rate of the movement is a linear function of the applied current. Any increment of the current produces (immediately, without any relaxing time) a faster movement of the actuator, by stopping the current flow the movement stops (the driving reaction and the film volume variation stops). Eq. 9 also indicates that the actuator is a positioning device: the same charge produces the

same displacement and the charge consumed during description of a movement of one degree (α/Q = k) is constant (independent of the applied current).

The above expressions can be normalized by mass unit of active conducting polymer reacting during actuation. This allows predicting the behaviour of every artificial muscle moving in a known electrolyte made of the same material whatever the geometry of the device is (shape, thickness, surface area, etc.). That means that the same change of the specific composition (according with reactions 1, 2 or 3) per unit time produce the same angular rate in devices having different geometry. This means that experiments from one muscle are only required in order to obtain this faradic characteristic of the CP.

The faradic control of the movement has been checked with different artificial muscles made of different polymers, exchanging both anions (Otero & Cortes, 2004) or cations (Valero et al., 2011).

8.2. Bending beam method

The bending beam method (Gere & Goodno, 2009; Timoshenko, 1925) is based on the analogy existing between a bending artificial muscle and a solid-state bending beam: the study of the forces generated at the interface between the non-conductive layer, keeping its volume constant during actuation, and the conducting polymer film, varying its volume locally.

This mechanical model assumes several characteristics related with the study of traditional mechanical bending beam: (I) the thickness of the beam is small compared to the minimum radius of curvature, (II) a linear relationship exists between stress and strain of the material and (III) the Young's modulus, Y, and the actuation expansion coefficient of the conducting polymer, α, keep constant: they do not depend on spatial location inside each layer.

The actuator curvature radius (R_∞ is the radius at the equilibrium and R_0 is the initial radius) is related to either, the Young's modulus (Y) and the thicknesses (h) of the conducting and non-conductive films (indicated by subscripts 1 and 2 respectively), and to the volume changes locally produced at the interface between both films α(t) (Pei & Inganäs, 1993b; Pei & Inganäs, 1993a; Pei & Inganäs, 1992b):

$$\frac{1}{R_\infty}-\frac{1}{R_0}=\frac{6\alpha_{(t)}}{\frac{\left(Y_1h_1^2-Y_2h_2^2\right)^2}{Y_1Y_2h_1h_2\left(h_1+h_2\right)}+4\left(h_1+h_2\right)} \tag{11}$$

Christophersen et al. (Christophersen et al., 2006) expanded the model by including strain and modulus variations along the direction of film thickness. Actuator's position, rate of the movement and force generated by the actuator (Alici & Huynh, 2006; Alici et al., 2006b) were simulated and applied to the design of biomimetic device (propulsion fins) (Alici et al., 2007). Du et al. (Du et al., 2010) have developed a general model for a multilayer system (N layers) to link the actuation strain of the actuator to the bending curvature.

8.3. Finite element method

The finite elements methodology is a well know mathematical treatment for engineering designs that can be applied to solve the movement of the artificial muscles too. Alici et al. (Alici et al., 2006a; Metz et al., 2006) developed a model based on a lumped-parameter mathematical model for trilayer actuators employing the analogy between thermal strain and the real strain (due to the insertion/extraction of ions inside the polymeric film) in polypyrrole actuators actuating in air. An optimization of the geometry was required, in order to obtain the greater output properties from a determined input voltage. Shapiro et al. (Shapiro & Smela, 2007) developed a two dimensional model (along a full area) to obtain curvature and angular moment from bilayer and trilayer actuators. Thus, they combined the results from the previous method (bending beam method) with finite element method to attain a solution. Another example of the employment of this method was carried out by Gutta et al. who applied it to the study the movement of a cylindrical ionic-polymer metal composite actuator (Gutta et al., 2011).

8.4. Equivalent transmission line model

Electrochemical systems, as many other systems, can be assimilated to electrical circuits and electrochemomechanical actuators have been treated by the equivalent transmission line method. This resource is a practical tool due to the great number of facilities available to the study of electrical circuits through different steps or modules. Such treatments are employed by engineers and physicists, or electrochemists, in order to explain the claimed capacitive behaviour of CP (Albery & Mount, 1993; Bisquert et al., 2000; Paasch, 2000). Ren et al. (Ren & Pickup, 1995) proposed equivalent electrical circuits to model the electron transport and electron transfer in composite pPy-PSS films based on Albery's works. Fang et al. (Fang et al., 2008; Yang et al., 2008) have developed a scalable method including dynamic actuation performance under a given voltage input, joining three different modules for different aspects of the actuator: electrochemical dynamics, stress-generation by charge and mechanical dynamics. Shoa et al. (Shoa et al., 2011) developed a dynamic electromechanical method for electrochemically driven conducting polymer actuators based on a 2-D impedance model using an RC transmission line equivalent circuit to predict the charge transfer during actuation. Besides, a mechanical model (based on the bending beam model) is considered after the equivalent circuit that simulates ion "diffusion" through the thickness and electronic resistance along the length (Shoa et al., 2010). If the angular movement is not linear along the full geometry of the actuator, the bending beam method has to be modified, for example for cantilever type conducting polymer actuators (Alici, 2009).

From all these kind of models, it is possible to employ only one or several of them at the same time in order to obtain the best required model (Woosoon et al., 2007).

9. Actuators applications

The investigation of these devices is mainly performed in academic laboratories. Nevertheless a rising number of applications and products are emerging with pioneering

companies that are being incorporated by large multinationals. So Creganna Tactx Medical and Bayer MaterialScience recently acquired a pair of companies working in the field, indicating the potential of these technologies. Also EAMEX from Japan is developing actuators for biomedical and robotic applications. NASA and ESA space agencies consider polymeric actuators as preferential technologies, and the European Scientific Network for Artificial Muscles (ESNAM) has started funded by the European Union. Many different applications can be found in literature. The following is a summary of a few of them, both macroscopic and microscopic.

- **Smart electronic textiles**: Although different strategies have been used to overcome problems like short lifetimes and high response times (Carpi & De Rossi, 2005; De Rossi et al., 2009; Wallace et al., 2007), much work has to be done in order to endow textiles with efficient and reliable actuating functions.
- **Braille displays**: Conducting polymers is one of the materials explored to develop low-cost and efficient displays for Braille text. Actual displays are close to achieve the required specs, but they have to overcome short cycling life (Ding et al., 2003; Spinks et al., 2003a).
- **Micropump**: It is possible to find in literature different types of micropumps made with conducting polymer actuators able to transport fluids at a microflow rate with high precission with low energy consumption (Kiefer et al., 2008; Kim et al., 2008; Morita et al.,2010 ; Naka et al., 2010; Ramírez-García & Diamond, 2007; Wu et al., 2005).
- **Propulsion or locomotion devices**: Systems based on trilayer configuration were proposed in aquatic devices (Alici et al., 2007; James et al., 2007; McGovern & et al., 2009; McGovern et al., 2010) for creating enough thrust for propulsion. Also bending actuators like cilia can be used in mini-robotic devices (Alici & Gunderson, 2009).
- **Microcatheters**: By depositing two conducting polymer films around a passive catheter and using a fast conductor solid state electrolyte, it is possible to control the movement of the catheter tip (DellaSanta et al., 1996; Shoa et al., 2008). This kind of microcatheters can be used in Optical Coherence Tomography to enable high-resolution 3D imaging (Lee et al., 2009).
- **Microactuators**: The electrochemical synthesis of conducting films and their electrochemical actuation (Wilson et al., 2007) are suitable for the construction different microdevices (He et al., 2007; Jager et al., 2001; Pede et al., 1998; Roemer et al., 2002) and microtools constituted by bilayers (Jager et al., 2000a; Jager et al., 2001; Jager et al., 2000b; Jager et al., 1999; Smela, 1999; Smela & Gadegaard, 1999; Smela et al., 1995; Smela et al., 1993) or trilayers (Gursel et al., 2009; Kiefer et al., 2008) using microelectronic technologies. These microactuators can be integrated in CMOS chips containing all the elements required to transport, contain and nurture biological cells (Jager et al., 2002; Smela et al., 2007).

10. Published papers and patents evolution

An indication of the initiation and fast growth of the field is given by bibliographic and patents evolution. As can be observed, the literature related to conducting polymers

actuators starts from 1990 (Fig. 4.a) reaching a maximum in 2006 with 45 papers, an excellent value for such a specific topic. After that, around 30 papers have been published every year. Fig. 4.b shows exponential evolution of citations with a value of almost 2000 in 2010. A similar evolution is observed in Fig. 4.c for patents, reaching a maximum in 2009 with 180 patents.

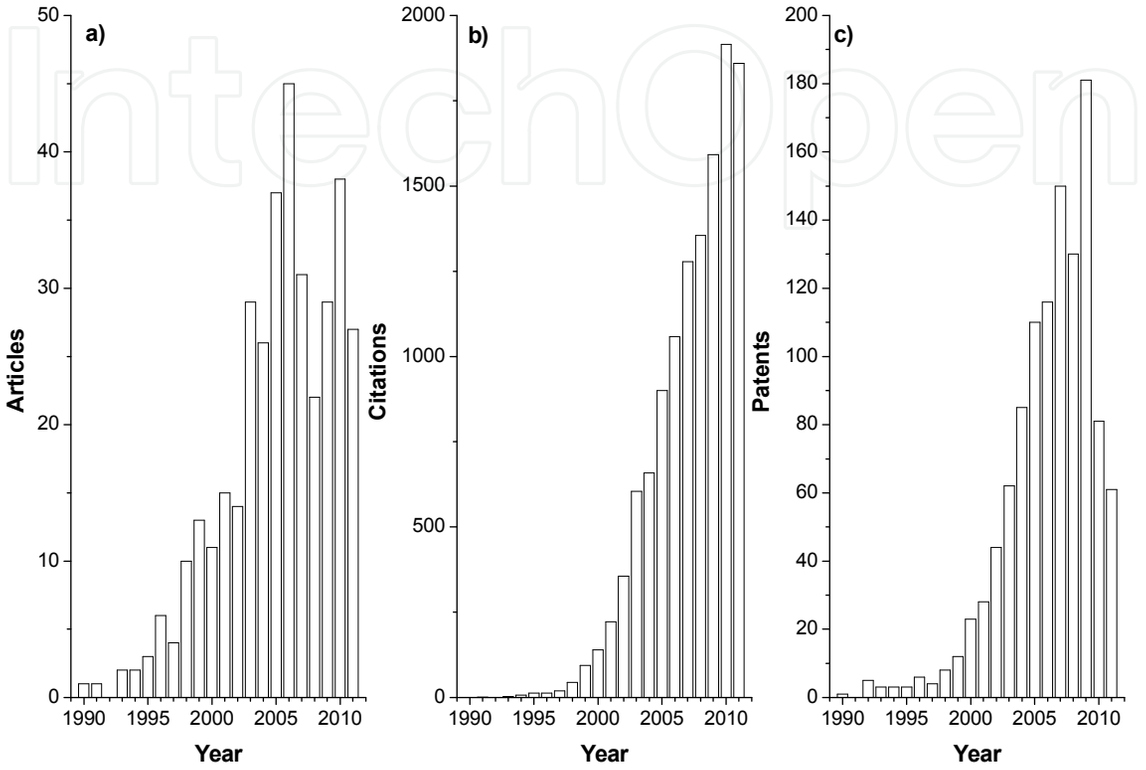

Figure 4. Evolution of a) published papers, b) citations and c) patents for "conducting polymer & actuator", from the ISI web of Knowledge® and Scopus®.

11. Future and challenges

Although a hard work has been performed, it does not exist yet an uncontroversial model for the description of the new reactive polymers and devices based on these reactive polymer gels whose composition and properties mimic those from artificial organs in mammals. New models should include concepts from very different fields of knowledge as electrochemistry, mechanics, polymer science and thermodynamics. In those systems, electrochemical reactions produce structural (conformational) changes in the polymeric chains and macroscopic volume changes related to the composition change of the material. Those aspects are not considered in the classical chemical kinetic models. Conducting polymer films should be used as models for the study and quantification of chemical kinetics under structural control with the aim to develop a new structural chemical model, able to quantify conformational changes and structural information in conducting polymers and in biological reactions originating life in living cells.

This model will allow the synthesis of new conducting polymers providing a more precise control of structural changes and intermolecular forces (polymer-ion interactions) with the

reaction. Those materials should be used in a new generation of polymeric actuators able to overcome current limitations, opening possibilities for new applications.

Other factors, such as configuration, manufacture of the actuators, design of the electric contacts or electrolytic media (solid or liquid) are also very important for the improvement of the electrochemomechanical actuators. This is a multidisciplinary field, a lot of work performed by specialists from different disciplines is required in order to attain a good control and modelling of both, devices and soft robots.

Author details

José G. Martínez, Joaquín Arias-Pardilla and Toribio F. Otero
Universidad Politécnica de Cartagena, Spain

Acknowledgement

Authors acknowledge financial support from Spanish Government (MCINN) Projects MAT2008-06702, MAT2011-24973, Seneca Foundation Project 08684/PI/08 and to the European network for Artificial Muscles ESNAM. Jose G. Martinez acknowledges Spanish Education Ministry for a FPU grant (AP2010-3460).

12. References

Ahonen, H. J., Lukkari, J. & Kankare, J. (2000). n- and p-doped poly(3,4-ethylenedioxythiophene): Two electronically conducting states of the polymer. *Macromolecules*, Vol. 33, No. 18, pp. 6787-6793, ISSN 0024-9297.

Albery, W. J. & Mount, A. R. (1993). Application of A Transmission-Line Model to Impedance Studies on A Poly(Vinylferrocene)-Modified Electrode. *J.Chem.Soc.Faraday T.*, Vol. 89, No. 2, pp. 327-331, ISSN 0956-5000.

Alici, G. & Huynh, N. N. (2006). Predicting force output of trilayer polymer actuators. *Sens. Actuat. A-Phys*, Vol. 132, No. 2, pp. 616-625, ISSN 0924-4247.

Alici, G., Metz, P. & Spinks, G. M. (2006a). A methodology towards geometry optimization of high performance polypyrrole (PPy) actuators. *Smart Mater.Struct.*, Vol. 15, No. 2, pp. 243-252, ISSN 0964-1726.

Alici, G., Mui, B. & Cook, C. (2006b). Bending modeling and its experimental verification for conducting polymer actuators dedicated to manipulation applications. *Sens. Actuat. A-Phys*, Vol. 126, No. 2, pp. 396-404, ISSN 0924-4247.

Alici, G., Spinks, G., Huynh, N. N., Sarmadi, L. & Minato, R. (2007). Establishment of a biomimetic device based on tri-layer polymer actuators-propulsion fins. *Bioinspir. Biomim.*, Vol. 2, No. 2, pp. S18-S30, ISSN 1748-3182.

Alici, G. (2009). An effective modelling approach to estimate nonlinear bending behaviour of cantilever type conducting polymer actuators. *Sens. Actuat. B-Chem*, Vol. 141, No. 1, pp. 284-292, ISSN 0925-4005.

Alici, G. & Gunderson, D. (2009). A bio-inspired robotic locomotion system based on conducting polymer actuators. In: *2009 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*. pp. 998-1004, IEEE, ISBN 978-1-4244-2852-6, New York.

Alici, G., Punning, A. & Shea, H. R. (2011). Enhancement of actuation ability of ionic-type conducting polymer actuators using metal ion implantation. *Actuat. B-Chem*, Vol. 157, No. 1, pp. 72-84, ISSN 0925-4005.

Arbizzani, C., Catellani, M., Mastragostino, M. & Mingazzini, C. (1995). N-doped and p-doped polydithieno[3,4-b-3',4'-d] thiophene - a narrow-band gap polymer for redox supercapacitors. *Electrochim. Acta*, Vol. 40, No. 12, pp. 1871-1876, ISSN 0013-4686.

Arias-Pardilla, J., Walker, W., Wudl, F. & Otero, T. F. (2010). Reduction and Oxidation Doping Kinetics of an Electropolymerized Donor-Acceptor Low-Bandgap Conjugated Copolymer. *J. Phys. Chem. B*, Vol. 114, No. 40, pp. 12777-12784, ISSN 1520-6106.

Arias-Pardilla, J., Plesse, C., Khaldi, A., Vidal, F., Chevrot, C. & Otero, T. F. (2011). Self-supported semi-interpenetrating polymer networks as reactive ambient sensors. *J. Electroanal. Chem.*, Vol. 652, No. 1-2, pp. 37-43, ISSN 1572-6657.

Balzani, V., Credi, A., Ferrer, B., Silvi, S. & Venturi, M. (2005). *Artificial molecular motors and machines: Design principles and prototype systems*, Springer-Verlag, ISBN 0340-1022, Berlin.

Baughman, R. H. (1996). Conducting polymer artificial muscles. *Synth. Met.*, Vol. 78, No. 3, pp. 339-353, ISSN 0379-6779.

Baughman, R. H., Cui, C. X., Zakhidov, A. A., Iqbal, Z., Barisci, J. N., Spinks, G. M., Wallace, G. G., Mazzoldi, A., De Rossi, D., Rinzler, A. G., Jaschinski, O., Roth, S. & Kertesz, M. (1999). Carbon nanotube actuators. *Science*, Vol. 284, No. 5418, pp. 1340-1344, ISSN 0036-8075.

Bay, L., West, K., Sommer-Larsen, P., Skaarup, S. & Benslimane, M. (2003). A conducting polymer artificial muscle with 12% linear strain. *Adv. Mater.*, Vol. 15, No. 4, pp. 310-313, ISSN 0935-9648.

Bieńkowski, K., Strawski, M. & Szklarczyk, M. (2011). The determination of the thickness of electrodeposited polymeric films by AFM and electrochemical techniques. *J. Electroanal. Chem.*, Vol. 662, No. 1, pp. 196-203, ISSN 1572-6657.

Bisquert, J., Belmonte, G. G., Santiago, F. F., Ferriols, N., Yamashita, M. & Pereira, E. C. (2000). Application of a distributed impedance model in the analysis of conducting polymer films. *Electrochem.Commun.*, Vol. 2, No. 8, pp. 601-605, ISSN 1388-2481.

Blonsky, P. M. & Meridian, I. (1997). Structurally stable gelled electrolytes, US Patent 5648011.

Carpi, F. & De Rossi, D. (2005). Electroactive polymer-based devices for e-textiles in biomedicine. *IEEE T. Inf. Technol. B*, Vol. 9, No. 3, pp. 295-318, ISSN 1089-7771.

Chiang, C. K., Fincher, C. R., Park, Y. W., Heeger, A. J., Shirakawa, H., Louis, E. J., Gau, S. C. & Macdiarmid, A. G. (1977). Electrical-Conductivity in Doped Polyacetylene. *Phys. Rev. Lett.*, Vol. 39, No. 17, pp. 1098-1101, ISSN 0031-9007.

Cho, M., Seo, H., Nam, J., Choi, H., Koo, J. & Lee, Y. (2007). High ionic conductivity and mechanical strength of solid polymer electrolytes based on NBr/ionic liquid and its

application to an electrochemical actuator. *Sens. Actuat. B-Chem*, Vol. 128, No. 1, pp. 70-74, ISSN 0925-4005.

Cho, M. S., Choi, J. J., Kim, T. S. & Lee, Y. (2011). In situ three-dimensional analysis of the linear actuation of polypyrrole micro-rod actuators using optical microscopy. *Sens. Actuat. B-Chem*, Vol. 156, No. 1, pp. 218-221, ISSN 0925-4005.

Christophersen, M., Shapiro, B. & Smela, E. (2006). Characterization and modeling of PPy bilayer microactuators - Part 1. Curvature. *Sens. Actuat. B-Chem*, Vol. 115, No. 2, pp. 596-609, ISSN 0925-4005.

Daerden, F. & Lefeber, D. (2002). Pneumatic Artificial Muscles: actuators for robotics and automation. *Eur. J. Mech. Environ. Eng.*, Vol. 47, No. 1, pp. 10-21, ISSN 1371-6980.

Davis, A. P. (1999). Nanotechnology - Synthetic molecular motors. *Nature*, Vol. 401, No. 6749, pp. 120-121, ISSN 0028-0836.

De Rossi, D., Carpi, F. & Galantini, F. (2009). Functional Materials for Wearable Sensing, Actuating and Energy Harvesting. In: *Biomedical Applications of Smart Materials, Nanotechnology and Micro/Nano Engineering*. pp. 247-256, Trans Tech Publications Ltd, ISBN 978-3-908158-23-3, Stafa-Zurich.

DellaSanta, A., Mazzoldi, A. & de Rossi, D. (1996). Steerable Microcatheters Actuated by Embedded Conducting Polymer Structures. *J. Intel. Mat. Syst. Str.*, Vol. 7, No. 3, pp. 292-300, ISSN 1045-389X.

DellaSanta, A., DeRossi, D. & Mazzoldi, A. (1997). Performance and work capacity of a polypyrrole conducting polymer linear actuator. *Synth. Met.*, Vol. 90, No. 2, pp. 93-100, ISSN 0379-6779.

Deshpande, S. D., Kim, J. & Yun, S. R. (2005a). New electro-active paper actuator using conducting polypyrrole: actuation behaviour in LiClO4 acetonitrile solution. *Synth. Met.*, Vol. 149, No. 1, pp. 53-58, ISSN 0379-6779.

Deshpande, S. D., Kim, J. & Yun, S. R. (2005b). Studies on conducting polymer electroactive paper actuators: Effect of humidity and electrode thickness. *Smart Mater. Struct.*, Vol. 14, No. 4, pp. 876-880, ISSN 0964-1726.

Ding, J., Liu, L., Spinks, G. M., Zhou, D., Wallace, G. G. & Gillespie, J. (2003). High performance conducting polymer actuators utilising a tubular geometry and helical wire interconnects. *Synth. Met.*, Vol. 138, No. 3, pp. 391-398, ISSN 0379-6779.

Dobbelin, M., Marcilla, R., Pozo-Gonzalo, C. & Mecerreyes, D. (2010). Innovative materials and applications based on poly(3,4-ethylenedioxythiophene) and ionic liquids. *J. Mater. Chem.*, Vol. 20, No. 36, pp. 7613-7622, ISSN 0959-9428.

Du, P., Lin, X. & Zhang, X. (2010). A multilayer bending model for conducting polymer actuators. *Sens. Actuat. A-Phys*, Vol. 163, No. 1, pp. 240-246, ISSN 0924-4247.

Fang, Y., Tan, X. O., Shen, Y. T., Xi, N. & Alici, G. (2008). A scalable model for trilayer conjugated polymer actuators and its experimental validation. *Mater. Sci. Eng., C*, Vol. 28, No. 3, pp. 421-428, ISSN 0928-4931.

Fuchiwaki, M., Tanaka, K. & Kaneto, K. (2009). Planate conducting polymer actuator based on polypyrrole and its application. *Sens. Actuat. A-Phys*, Vol. 150, No. 2, pp. 272-276, ISSN 0924-4247.

Garcia-Cordova, F., Valero, L., Ismail, Y. A. & Otero, T. F. (2011). Biomimetic polypyrrole based all three-in-one triple layer sensing actuators exchanging cations. *J. Mater. Chem.*, Vol. 21, No. 43, pp. 17265-17272, ISSN 0959-9428.

Gere, J. M. & Goodno, B. J. (2009). *Mechanics of Materials 4th Ed.*, Cengage Learning, ISBN 0534553974, Toronto.

Gimenez, P., Mukai, K., Asaka, K., Hata, K., Oike, H. & Otero, T. F. (2012). Capacitive and faradic charge components in high-speed carbon nanotube actuator. *Electrochim. Acta*, Vol. 60, No. 177-183, ISSN 0013-4686.

Guo, Y., Yu, G. & Liu, Y. (2010). Functional Organic Field-Effect Transistors. *Adv. Mater.*, Vol. 22, No. 40, pp. 4427-4447, ISSN 1521-4095.

Gursel, A., Valerie, D., Philippe, R. & Geoff, S. (2009). Conducting polymer microactuators operating in air. *J. Micromech. Microeng.*, Vol. 19, No. 2, pp. 025017, ISSN 0960-1317.

Gutta, S., Realmuto, J., Woosoon, Y. & Kim, K. J. (2011). *Dynamic model of a cylindrical ionic polymer-metal composite actuator*. Proceedings of 8th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI), Incheon.

Han, G. & Shi, G. (2006). Electrochemical actuator based on single-layer polypyrrole film. *Sens. Actuat. B-Chem*, Vol. 113, No. 1, pp. 259-264, ISSN 0925-4005.

Hara, S., Zama, T., Sewa, S., Takashima, W. & Kaneto, K. (2003). Polypyrrole-metal coil composites as fibrous artificial muscles. *Chem. Lett.*, Vol. 32, No. 9, pp. 800-801, ISSN 0366-7022.

Hara, S., Zama, T., Ametani, A., Takashima, W. & Kaneto, K. (2004). Enhancement in electrochemical strain of a polypyrrole-metal composite film actuator. *J. Mater. Chem.*, Vol. 14, No. 18, pp. 2724-2725, ISSN 0959-9428.

Hara, S., Zama, T., Tanaka, N., Takashima, W. & Kaneto, K. (2005). Artificial fibular muscles with 20% strain based on polypyrrole-metal coil composites. *Chem.Lett.*, Vol. 34, No. 6, pp. 784-785, ISSN 0366-7022.

Hara, S., Zama, T., Takashima, W. & Kaneto, K. (2006). Tris (trifluoromethylsulfonyl)methide-doped polypyrrole as a conducting polymer actuator with large electrochemical strain. *Synth.Met.*, Vol. 156, No. 2-4, pp. 351-355, ISSN 0379-6779.

He, X. M., Li, C., Chen, F. G. & Shi, G. Q. (2007). Polypyrrole microtubule actuators for seizing and transferring microparticles. *Adv. Funct. Mater.*, Vol. 17, No. 15, pp. 2911-2917, ISSN 1616-301X.

Heuer, H. W., Wehrmann, R. & Kirchmeyer, S. (2002). Electrochromic window based on conducting poly (3,4-ethylenedioxythiophene)poly(styrene sulfonate). *Adv. Funct. Mater.*, Vol. 12, No. 2, pp. 89-94, ISSN 1616-301X.

Higgins, S. J., Lovell, K. V., Rajapakse, R. M. G. & Walsby, N. M. (2003). Grafting and electrochemical characterisation of poly-(3,4-ethylenedioxythiophene) films, on Nafion and on radiation-grafted polystyrenesulfonate-polyvinylidene fluoride composite surfaces. *J. Mater. Chem.*, Vol. 13, No. 10, pp. 2485-2489, ISSN 0959-9428.

Hillman, A. R., Loveday, D. C., Swann, M. J., Eales, R. M., Hamnett, A., Higgins, S. J., Bruckenstein, S. & Wilde, C. P. (1989). Charge Transport in Electroactive Polymer-Films. *Faraday Discuss. Chem. Soc.*, Vol. 88, No. 151-163, ISSN 0301-7249.

Huang, W. S., Humphrey, B. D. & MacDiarmid, A. G. (1986). Polyaniline, A Novel Conducting Polymer - Morphology and Chemistry of Its Oxidation and Reduction in Aqueous-Electrolytes. *J. Chem. Soc., Faraday Trans. I*, Vol. 82, No. 2385-2400, ISSN 0300-9599.

Huang, Y., Liang, J. & Chen, Y. (2012). The application of graphene based materials for actuators. *J. Mater. Chem.*, Vol. 22, No. 9, pp. 3671-3679, ISSN 0959-9428.

Ikushima, K., John, S., Yokoyama, K. & Nagamitsu, S. (2009). A practical multilayered conducting polymer actuator with scalable work output. *Smart. Mater. Struct.*, Vol. 18, No. 9, pp. 9, ISSN 0964-1726.

Inzelt, G. (2008). Redox Transformations and Transport Processes. In: *Conducting Polymers*, Scholz, F. pp. 169-224, Springer-Verlag Berlin, ISBN 9783540759294, Heidelberg (Germany).

Inzelt, G. (2011). Rise and rise of conducting polymers. *J. Solid State Electrochem.*, Vol. 15, No. 7-8, pp. 1711-1718, ISSN 1432-8488.

Ismail, Y. A., Martínez, J. G., Harrasi, A. S. A., Kim, S. J. & Otero, T. F. (2011). Sensing characteristics of a conducting polymer/hydrogel hybrid microfiber artificial muscle. *Actuat. B-Chem*, Vol. No. 0, pp. ISSN 0925-4005.

Jager, E. W. H., Smela, E., Inganäs, O. & Lundstrom, I. (1999). Polypyrrole microactuators. *Synth. Met.*, Vol. 102, No. 1-3, pp. 1309-1310, ISSN 0379-6779.

Jager, E. W. H., Inganäs, O. & Lundstrom, I. (2000a). Microrobots for micrometer-size objects in aqueous media: Potential tools for single-cell manipulation. *Science*, Vol. 288, No. 5475, pp. 2335-2338, ISSN 0036-8075.

Jager, E. W. H., Smela, E. & Inganäs, O. (2000b). Microfabricating conjugated polymer actuators. *Science*, Vol. 290, No. 5496, pp. 1540-1545, ISSN 0036-8075.

Jager, E. W. H., Inganäs, O. & Lundstrom, I. (2001). Perpendicular actuation with individually controlled polymer microactuators. *Adv. Mater.*, Vol. 13, No. 1, pp. 76-79, ISSN 0935-9648.

Jager, E. W. H., Immerstrand, C., Peterson, K. H., Magnusson, K.-E., Lundström, I. & Inganäs, O. (2002). The Cell Clinic: Closable Microvials for Single Cell Studies. *Biomed. Microdev*, Vol. 4, No. 3, pp. 177-187, ISSN 1387-2176.

James, T., Patrick, A., Timothy, F., Angela, C., Mike Del, Z. & Ian, H. (2007). The application of conducting polymers to a biorobotic fin propulsor. *Bioinspir. Biomim.*, Vol. 2, No. 2, pp. S6, ISSN 1748-3190.

John, S., Alici, G. & Cook, C. (2008). *Frequency response of polypyrrole trilayer actuator displacement*. Proceedings of Electroactive Polymer Actuators and Devices (Eapad) 2008, San Diego (USA).

Kaneto, K., Suematsu, H. & Yamato, K. (2008). Training effect and fatigue in polypyrrole-based artificial muscles. *Bioinspir. Biomim.*, Vol. 3, No. 3, pp. 035005, ISSN 1748-3182.

Kaneto, K., Suematsu, H. & Yamato, K. (2009). Conducting Polymer Soft Actuators based on Polypyrrole-Training Effect and Fatigue. In: *Artificial Muscle Actuators Using Electroactive Polymers*, Vincenzini, P., Bar-Cohen, Y. & Carpi, F. pp. 122-130, Trans Tech Publications Inc., ISBN 1662-0356, Stafa-Zuerich, Switzerland.

Kiefer, R., Chu, S. Y., Kilmartin, P. A., Bowmaker, G. A., Cooney, R. P. & Travas-Sejdic, J. (2007). Mixed-ion linear actuation behaviour of polypyrrole. *Electrochim. Acta*, Vol. 52, No. 7, pp. 2386-2391, ISSN 0013-4686.

Kiefer, R., Mandviwalla, X., Archer, R., Tjahyono, S. S., Wang, H., MacDonald, B., Bowmaker, G. A., Kilmartin, P. A. & Travas-Sejdic, J. (2008). *The application of polypyrrole trilayer actuators in microfluidics and robotics*. Proceedings of Electroactive Polymer Actuators and Devices (Eapad).

Kim, J. H., Lau, K. T., Shepherd, R., Wu, Y., Wallace, G. & Diamond, D. (2008). Performance characteristics of a polypyrrole modified polydimethylsiloxane (PDMS) membrane based microfluidic pump. *Sensors and Actuators A: Physical*, Vol. 148, No. 1, pp. 239-244, ISSN 0924-4247.

Kim, L. T. T., Sel, O., Biemme-Chouvy, C., Gabrielli, C., Laberty-Robert, C., Perrot, H. & Sanchez, C. (2010). Proton transport properties in hybrid membranes investigated by ac-electrogravimetry. *Electrochem.Commun.*, Vol. 12, No. 8, pp. 1136-1139, ISSN 1388-2481.

Klauk, H., Ed. (2006). *Organic Electronics: Materials, Manufacturing, and Applications* Wiley-VCH Verlag, ISBN 978-3-527-31264-1, Weinheim.

Kuttel, C., Stemmer, A. & Wei, X. (2009). Strain response of polypyrrole actuators induced by redox agents in solution. *Sens. Actuat. B-Chem*, Vol. 141, No. 2, pp. 478-484, ISSN 0925-4005.

Lee, K. K. C., Munce, N. R., Shoa, T., Charron, L. G., Wright, G. A., Madden, J. D. & Yang, V. X. D. (2009). Fabrication and characterization of laser-micromachined polypyrrole-based artificial muscle actuated catheters. *Sens. Actuat. A-Phys*, Vol. 153, No. 2, pp. 230-236, ISSN 0924-4247.

Li, W. G., Johnson, C. L. & Wang, H. L. (2004). Preparation and characterization of monolithic polyaniline-graphite composite actuators. *Polymer*, Vol. 45, No. 14, pp. 4769-4775, ISSN 0032-3861.

Lu, W., Fadeev, A. G., Qi, B. H., Smela, E., Mattes, B. R., Ding, J., Spinks, G. M., Mazurkiewicz, J., Zhou, D. Z., Wallace, G. G., MacFarlane, D. R., Forsyth, S. A. & Forsyth, M. (2002). Use of ionic liquids for pi-conjugated polymer electrochemical devices. *Science*, Vol. 297, No. 5583, pp. 983-987, ISSN 0036-8075.

Lyutov, V., Tsakova, V. & Bund, A. (2011). Microgravimetric study on the formation and redox behavior of poly(2-acrylamido-2-methyl-1-propanesulfonate)-doped thin polyaniline layers. *Electrochim. Acta*, Vol. 56, No. 13, pp. 4803-4811, ISSN 0013-4686.

Mazzoldi, A., Degl'Innocenti, C., Michelucci, M. & De Rossi, D. (1998). Actuative properties of polyaniline fibers under electrochemical stimulation. *Mater. Sci. Eng., C*, Vol. 6, No. 1, pp. 65-72, ISSN 0928-4931.

McGovern, S. & et al. (2009). Finding NEMO (novel electromaterial muscle oscillator): a polypyrrole powered robotic fish with real-time wireless speed and directional control. *Smart Mater. Struct.*, Vol. 18, No. 9, pp. 095009, ISSN 0964-1726.

McGovern, S. T., Abbot, M., Emery, R., Alici, G., Truong, V. T., Spinks, G. M. & Wallace, G. G. (2010). Evaluation of thrust force generated for a robotic fish propelled with polypyrrole actuators. *Polym. Int.*, Vol. 59, No. 3, pp. 357-364, ISSN 0959-8103.

Metz, P., Alici, G. & Spinks, G. M. (2006). A finite element model for bending behaviour of conducting polymer electromechanical actuators. *Sens. Actuat. A-Phys*, Vol. 130, No. 1-11, ISSN 0924-4247.

Morita, T., Chida, Y., Hoshino, D., Fujiya, T. & Nishioka, Y. Fabrication and characterization of a polypyrrole soft actuator having corrugated structures. *Mol. Cryst. Liq. Cryst.*, Vol. 519, No. 121-127, ISSN 1542-1406.

Morita, T., Chida, Y., Hoshino, D., Fujiya, T. & Nishioka, Y. (2010). Fabrication and Characterization of a Polypyrrole Soft Actuator Having Corrugated Structures. *Mol. Cryst. Liq. Cryst.*, Vol. 519, No. 121-127, ISSN 1542-1406.

Mukai, K., Asaka, K., Hata, K., Otero, T. F. & Oike, H. (2011). High-Speed Carbon Nanotube Actuators Based on an Oxidation/Reduction Reaction. *Chem.-Eur. J.*, Vol. 17, No. 39, pp. 10965-10971, ISSN 1521-3765.

Mutlu, R. & Alici, G. (2010). A Multistable Linear Actuation Mechanism Based on Artificial Muscles. *J. Mech. Des.*, Vol. 132, No. 11, pp. 111001, ISSN 1050-0472.

Naka, Y., Fuchiwaki, M. & Tanaka, K. (2010). A micropump driven by a polypyrrole-based conducting polymer soft actuator. *Polym. Int.*, Vol. 59, No. 3, pp. 352-356, ISSN 1097-0126.

Nakano, T. & Okamoto, Y. (2001). Synthetic Helical Polymers: Conformation and Function. *Chem. Rev.*, Vol. 101, No. 12, pp. 4013-4038, ISSN

Okamoto, T., Tada, K. & Onoda, M. (2000). Bending machine using anisotropic polypyrrole films. *Jpn. J. Appl. Phys. 1*, Vol. 39, No. 5A, pp. 2854-2858, ISSN 0021-4922.

Okamoto, T., Kato, Y., Tada, K. & Onoda, M. (2001). Actuator based on doping/undoping-induced volume change in anisotropic polypyrrole film. *Thin Solid Films*, Vol. 393, No. 1-2, pp. 383-387, ISSN 0040-6090.

Okuzaki, H. & Hattori, T. (2003). Electrically induced anisotropic contraction of polypyrrole films. *Synth. Met.*, Vol. 135-136, No. 45-46, ISSN 0379-6779.

Okuzaki, H. (2008). A biomorphic origami actuator fabricated by folding a conducting paper. *J. Phys. Conf. Ser.*, Vol. 127, No. 1, pp. 012001, ISSN 1742-6596.

Onoda, M., Okamoto, T., Tada, K. & Nakayama, H. (1999a). Polypyrrole films with anisotropy for artificial muscles and examination of bending behavior. *Jpn. J. Appl. Phys. 2*, Vol. 38, No. 9AB, pp. L1070-L1072, ISSN 0021-4922.

Onoda, M., Tada, K. & Nakayama, H. (1999b). Polypyrrole films with anisotropy. *Synth. Met.*, Vol. 102, No. 1-3, pp. 1321-1322, ISSN 0379-6779.

Onoda, M. & Tada, K. (2004). Anisotropic bending machine using conducting polypyrrole. *IEICE Trans. Electron.*, Vol. E87C, No. 2, pp. 128-135, ISSN 0916-8524.

Onoda, M., Shonaka, H. & Tada, K. (2005). A self-organized bending-beam electrochemical actuator. *Curr. Appl. Phys.*, Vol. 5, No. 2, pp. 194-201, ISSN 1567-1739.

Orata, D. & Buttry, D. A. (1987). Determination of ion populations and solvent content as functions of redox state and pH in polyaniline. *J. Am. Chem. Soc.*, Vol. 109, No. 12, pp. 3574-3581, ISSN 0002-786.

Otero, T., Cascales, J. & Fernandez-Romero, A. (2007a). *Attempting a classification for electrical polymeric actuators*. Proceedings of Electroactive Polymer Actuators and Devices (EAPAD), San Diego.

Otero, T. F., Angulo, E., Rodriguez, J. & Santamaria, C. (1992a). Electrochemomechanical Properties from A Bilayer - Polypyrrole Nonconducting and Flexible Material Artificial Muscle. *J. Electroanal. Chem.*, Vol. 341, No. 1-2, pp. 369-375, ISSN 0022-0728.

Otero, T. F., Angulo, E., Rodriguez, J. & Santamaria, C. (1992b). Dispositivos laminares que emplean polímeros conductores capaces de provocar movimientos mecánicos, ES Patent 2 048 086.

Otero, T. F., Rodriguez, J. & Santamaria, C. (1992c). Músculos artificiales formados por multicapas: polímeros conductores-no conductores, ES Patent 2 062 930.

Otero, T. F. (1999). Conducting polymers, electrochemistry, and biomimicking processes. In: *Modern Aspects of Electrochemistry*, Bockris, J.O.M., White, R.E. & Conway, B.E. pp. 307-434, Kluwer Academic/Plenum Publ, ISBN 0076-9924, New York.

Otero, T. F. (2000). Biomimicking materials with smart polymers. In: *Structural biological materials. Design and structure-properties relationships*, Elices, M. & Cahn, R.W. pp. 187-220, Pergamon Materials Series, ISBN 0080434169, Amsterdam (The Netherlands).

Otero, T. F. & Cortes, M. T. (2003a). Artificial muscles with tactile sensitivity. *Adv. Mater.*, Vol. 15, No. 4, pp. 279-282, ISSN 0935-9648.

Otero, T. F. & Cortes, M. T. (2003b). A sensing muscle. *Sens. Actuators, B*, Vol. 96, No. 1-2, pp. 152-156, ISSN 0925-4005.

Otero, T. F. & Cortes, M. T. (2004). Artificial muscle: movement and position control. *Chem. Commun.*, Vol. No. 3, pp. 284-285, ISSN 1359-7345.

Otero, T. F., Arenas, G. V. & Cascales, J. J. L. (2006). Effect of the doping ion on the electrical response of a free-standing polypyrrole strip subjected to different preloads: Perspectives and limitations associated with the use of these devices as actuators. *Macromolecules*, Vol. 39, No. 26, pp. 9551-9556, ISSN 0024-9297.

Otero, T. F. & Broschart, M. (2006). Polypyrrole artificial muscles: a new rhombic element. Construction and electrochemomechanical characterization. *J. Appl. Electrochem.*, Vol. 36, No. 2, pp. 205-214, ISSN 0021-891X.

Otero, T. F. (2007). Artificial muscles. In: *Handbook of Conducting Polymers*, Skotheim, T.A., Elsenbaumer, R.L. & Reynolds, J.R. pp. 591-623, CRC Press, ISBN Boca Raton.

Otero, T. F., Cortes, M. T. & Arenas, G. V. (2007b). Linear movements from two bending triple-layers. *Electrochim. Acta*, Vol. 53, No. 3, pp. 1252-1258, ISSN 0013-4686.

Otero, T. F., Lopez Cascales, J. J. & Vazquez Arenas, G. (2007c). Mechanical characterization of free-standing polypyrrole film. *Mater. Sci. Eng., C*, Vol. 27, No. 1, pp. 18-22, ISSN 0928-4931.

Otero, T. F. (2008). Artificial Muscles, Sensing and Multifunctionality. In: *Intelligent Materials*, Shahinpoor, M. & Schenider, H.-J. pp. 142-190, Royal Society of Chemistry, ISBN 9780854043354, Cambridge (U.K.).

Otero, T. F. (2009). Soft, wet, and reactive polymers. Sensing artificial muscles and conformational energy. *J. Mater. Chem.*, Vol. 19, No. 681-689, ISSN 0959-9428.

Otero, T. F. (2011). From Electrochemically-Driven Conformational Polymeric States to Macroscopic Sensing and Tactile Muscles. In: *From Non-Covalent Assemblies to Molecular Machines*, Sauvage, J.-P. & Gaspard, P. pp. Wiley-VCH Verlag & Co., ISBN Weinheim, Germany.

Otero, T. F., Arias-Pardilla, J., Herrera, H., Segura, J. L. & Seoane, C. (2011). Electropolymerization of naphthaleneamidinemonoimide-modified poly(thiophene). *Phys. Chem. Chem. Phys.*, Vol. 13, No. 37, pp. 16513-16516, ISSN 1463-9076.

Otero, T. F., Sánchez, J. J. & Martinez, J. G. (2012) Biomimetic Dual Sensing-Actuators based on Conducting Polymers. Galvanostatic Theoretical Model for Actuators Sensing Temperature. J. Phys. Chem. B, Vol 116, No. 17, pp. 5279-5290, ISSN 1089-5647.

Ouyang, P. R., Tjiptoprodjo, R. C., Zhang, W. J. & Yang, G. S. (2008). Micro-motion devices technology: The state of arts review. *Int. J. Adv. Manuf. Technol.*, Vol. 38, No. 5-6, pp. 463-478, ISSN 0268-3768.

Paasch, G. (2000). The transmission line equivalent circuit model in solid-state electrochemistry. *Electrochem. Commun.*, Vol. 2, No. 5, pp. 371-375, ISSN 1388-2481.

Park, S. J., Cho, M. S., Nam, J. D., Kim, I. H., Choi, H. R., Koo, J. C. & Lee, Y. (2009). The linear stretching actuation behavior of polypyrrole nanorod in AAO template. *Sens. Actuat. B-Chem*, Vol. 135, No. 2, pp. 592-596, ISSN 0925-4005.

Pede, D., Smela, E., Johansson, T., Johansson, M. & Inganäs, O. (1998). A general-purpose conjugated-polymer device array for imaging. *Adv. Mater.*, Vol. 10, No. 3, pp. 233-237, ISSN 0935-9648.

Pei, Q. & Inganäs, O. (1993a). Electrochemical applications of the bending beam method; a novel way to study ion transport in electroactive polymers. *Solid State Ionics*, Vol. 60, No. 1-3, pp. 161-166, ISSN 0167-2738.

Pei, Q. & Inganäs, O. (1993b). Electrochemical applications of the bending beam method. 2. Electroshrinking and slow relaxation in polypyrrole. *J. Phys. Chem.*, Vol. 97, No. 22, pp. 6034-6041, ISSN 0022-3654.

Pei, Q. B. & Inganäs, O. (1992a). Conjugated Polymers and the Bending Cantilever Method - Electrical Muscles and Smart Devices. *Adv. Mater.*, Vol. 4, No. 4, pp. 277-278, ISSN 0935-9648.

Pei, Q. B. & Inganäs, O. (1992b). Electrochemical Applications of the Bending Beam Method .1. Mass-Transport and Volume Changes in Polypyrrole During Redox. *J. Phys. Chem.*, Vol. 96, No. 25, pp. 10507-10514, ISSN 0022-3654.

Perepichka, I. F. & Perepichka, D. F., Eds. (2009). *Handbook of Thiophene-Based Materials: Applications in Organic Electronics and Photonics*. John Wiley & Sons Ltd., ISBN 978-0-470-05732-2, Chichester (UK).

Plesse, C., Vidal, F., Randriamahazaka, H., Teyssie, D. & Chevrot, C. (2005). Synthesis and characterization of conducting interpenetrating polymer networks for new actuators. *Polymer*, Vol. 46, No. 18, pp. 7771-7778, ISSN 0032-3861.

Plesse, C., Vidal, F., Teyssie, D. & Chevrot, C. (2009). Conducting IPN Fibers: a new design for linear actuation in open air. In: *Artificial Muscle Actuators using Electroactive Polymers* Vincenzini, P., Bar-Cohen, Y. & Carpi, F. pp. 53-58, Trans Tech Publicactions Ltd., ISBN 1662-0356, Stafa-Zurich (Switzerland).

Plesse, C., Vidal, F., Teyssie, D. & Chevrot, C. (2010). Conducting polymer artificial muscle fibres: toward an open air linear actuation. *Chem. Commun.*, Vol. 46, No. 17, pp. 2910-2912, ISSN 1359-7345.

Ramírez-García, S. & Diamond, D. (2007). Biomimetic, low power pumps based on soft actuators. *Sens. Actuat. A-Phys*, Vol. 135, No. 1, pp. 229-235, ISSN 0924-4247.

Ranger, M. & Leclerc, M. (1998). Optical and electrical properties of fluorene-based pi-conjugated polymers. *Can. J. Chem.*, Vol. 76, No. 11, pp. 1571-1577, ISSN 0008-4042.

Ren, X. & Pickup, P. G. (1995). Impedance measurements of ionic conductivity as a probe of structure in electrochemically deposited polypyrrole films. *J. Electroanal. Chem.*, Vol. 396, No. 1–2, pp. 359-364, ISSN 1572-6657.

Roemer, M., Kurzenknabe, T., Oesterschulze, E. & Nicoloso, N. (2002). Microactuators based on conducting polymers. *Anal. Bioanal. Chem.*, Vol. 373, No. 8, pp. 754-757, ISSN 1618-2642.

Sansinena, J. M., Olazabal, V., Otero, T. F., daFonseca, C. N. P. & DePaoli, M. A. (1997). A solid state artificial muscle based on polypyrrole and a solid polymeric electrolyte working in air. *Chem. Commun.*, Vol. No. 22, pp. 2217-2218, ISSN 1359-7345.

Sansiñena, J. M., Gao, J. B. & Wang, H. L. (2003). High-performance, monolithic polyaniline electrochemical actuators. *Adv. Funct. Mater.*, Vol. 13, No. 9, pp. 703-709, ISSN 1616-301X.

Shakuda, S., Morita, S., Kawai, T. & Yoshino, K. (1993). Dynamic Characteristics of Bimorph with Conducting Polymer Gel. *Jpn. J. Appl. Phys. 1*, Vol. 32, No. 11A, pp. 5143-5146, ISSN 0021-4922.

Shapiro, B. & Smela, E. (2007). Bending Actuators with Maximum Curvature and Force and Zero Interfacial Stress. *J. Intel. Mat. Syst. Str.*, Vol. 18, No. 2, pp. 181-186, ISSN 1045-389X.

Shirakawa, H., Louis, E. J., Macdiarmid, A. G., Chiang, C. K. & Heeger, A. J. (1977). Synthesis of Electrically Conducting Organic Polymers - Halogen Derivatives of Polyacetylene, (Ch)X. *J. Chem. Soc., Chem. Commun.*, Vol. No. 16, pp. 578-580, ISSN 0022-4936.

Shoa, T., Madden, J. D., Fekri, N., Munce, N. R. & Yang, V. X. D. (2008). *Conducting polymer based active catheter for minimally invasive interventions inside arteries*. Proceedings of 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2008.

Shoa, T., Madden, J. D. W., Munce, N. R. & Yang, V. (2010). Analytical modeling of a conducting polymer-driven catheter. *Polym.Int.*, Vol. 59, No. 3, pp. 343-351, ISSN 1097-0126.

Shoa, T., Yoo, D. S., Walus, K. & Madden, J. D. W. (2011). A Dynamic Electromechanical Model for Electrochemically Driven Conducting Polymer Actuators. *IEEE ASME Trans. Mechatronics*, Vol. 16, No. 1, pp. 42-49, ISSN 1083-4435.

Smela, E., Inganäs, O., Pei, Q. B. & Lundstrom, I. (1993). Electrochemical Muscles - Micromachining Fingers and Corkscrews. *Adv. Mater.*, Vol. 5, No. 9, pp. 630-632, ISSN 0935-9648.

Smela, E., Inganäs, O. & Lundstrom, I. (1995). Controlled Folding of Micrometer-Size Structures. *Science*, Vol. 268, No. 5218, pp. 1735-1738, ISSN 0036-8075.

Smela, E. (1999). A microfabricated movable electrochromic "pixel" based on polypyrrole. *Adv. Mater.*, Vol. 11, No. 16, pp. 1343-1345, ISSN 0935-9648.

Smela, E. & Gadegaard, N. (1999). Surprising volume change in PPy(DBS): An atomic force microscopy study. *Adv. Mater.*, Vol. 11, No. 11, pp. 953-957, ISSN 0935-9648.

Smela, E. & Gadegaard, N. (2001). Volume change in polypyrrole studied by atomic force microscopy. *J. Phys. Chem. B*, Vol. 105, No. 39, pp. 9395-9405, ISSN 1089-5647.

Smela, E., Christophersen, M., Prakash, S. B., Urdaneta, M., Dandin, M. & Abshire, P. (2007). *Integrated cell-based sensors and "cell clinics" utilizing conjugated polymer actuators*. Proceedings of SPIE - The International Society for Optical Engineering.

Smith, E. B. (2004). *Basic Chemical Thermodynamics*, Imperial College Press., ISBN 1-86094-445-0, London.

So, F., Ed. (2010). *Organic electronics : materials, processing, devices and applications*. CRC Press, ISBN 978-1-4200-7290-7, Boca Raton (USA).

Song, M. K., Cho, J. Y., Cho, B. W. & Rhee, H. W. (2002). Characterization of UV-cured gel polymer electrolytes for rechargeable lithium batteries. *J. Power Sources*, Vol. 110, No. 1, pp. 209-215, ISSN 0378-7753.

Spinks, G. M., Liu, L., Wallace, G. G. & Zhou, D. (2002). Strain Response from Polypyrrole Actuators under Load. *Adv. Funct. Mater.*, Vol. 12, No. 6-7, pp. 437-440, ISSN 1616-3028.

Spinks, G. M., Wallace, G. G., Ding, J., Zhou, D., Xi, B. & Gillespie, J. (2003a). *Ionic liquids and polypyrrole helix tubes: bringing the electronic Braille screen closer to reality*. Proceedings of Smart Structures and Materials 2003: Electroactive Polymer Actuators and Devices (EAPAD), San Diego, USA.

Spinks, G. M., Zhou, D. Z., Liu, L. & Wallace, G. G. (2003b). The amounts per cycle of polypyrrole electromechanical actuators. *Smart. Mater. Struct.*, Vol. 12, No. 3, pp. 468-472, ISSN 0964-1726.

Takashima, W., Uesugi, T., Fukui, M., Kaneko, M. & Kaneto, K. (1997). Mechanochemoelectrical effect of polyaniline film. *Synth. Met.*, Vol. 85, No. 1-3, pp. 1395-1396, ISSN 0379-6779.

Takashima, W., Pandey, S. S. & Kaneto, K. (2003). Bi-ionic actuator by polypyrrole films. *Synth. Met.*, Vol. 135, No. 1-3, pp. 61-62, ISSN 0379-6779.

Timoshenko, S. (1925). Analysis of bi-metal thermostats. *J. Opt. Soc. Am.*, Vol. 11, No. 3, pp. 233-255, ISSN 0093-4119.

Torresi, R. M. & Maranhao, S. L. D. (1999). Anion and solvent exchange as a function of the redox states in polyaniline films. *J. Electrochem. Soc.*, Vol. 146, No. 11, pp. 4179-4182, ISSN 0013-4651.

Tsai, E. W., Pajkossy, T., Rajeshwar, K. & Reynolds, J. R. (1988). Anion-Exchange Behavior of Polypyrrole Membranes. *J. Phys. Chem.*, Vol. 92, No. 12, pp. 3560-3565, ISSN 0022-3654.

Valero Conzuelo, L., Arias-Pardilla, J., Cauigh-Rodríguez, J. V., Smit, M. A. & Otero, T. F. (2010). Sensing and Tactile Artificial Muscles from Reactive Materials. *Sensors*, Vol. 10, No. 2638-2674, ISSN 1424-8220.

Valero, L., Arias-Pardilla, J., Smit, M., Cauich-Rodríguez, J. & Otero, T. F. (2010). Polypyrrole Free-Standing electrodes sense temperature or current during reaction. *Polym. Int.*, Vol. 59, No. 337-342, ISSN 1097-0126.

Valero, L., Arias-Pardilla, J., Cauich-Rodríguez, J., Smit, M. A. & Otero, T. F. (2011). Characterization of the movement of polypyrrole-dodecylbenzenesulfonate-

perchlorate/tape artificial muscles. Faradaic control of reactive artificial molecular motors and muscles. *Electrochim. Acta*, Vol. 56, No. 10, pp. 3721-3726, ISSN 0013-4686.

Vidal, F., Popp, J. F., Plesse, C., Chevrot, C. & Teyssie, D. (2003). Feasibility of conducting semi-interpenetrating networks based on a poly(ethylene oxide) network and poly(3,4-ethylenedioxythiophene) in actuator design. *J. Appl. Polym. Sci.*, Vol. 90, No. 13, pp. 3569-3577, ISSN 0021-8995.

Vidal, F., Plesse, C., Palaprat, G., Juger, J., Citerin, J., Kheddar, A., Chevrot, C. & Teyssie, D. (2009). Synthesis and Characterization of IPNs for Electrochemical Actuators. In: *Artificial Muscle Actuators Using Electroactive Polymers*, Vincenzini, P., BarCohen, Y. & Carpi, F. pp. 8-17, Trans Tech Publications Ltd, ISBN 978-3-908158-27-1, Stafa-Zurich.

Vidal, F., Plesse, C., Aubert, P. H., Beouch, L., Tran-Van, F. o., Palaprat, G., Verge, P., Yammine, P., Citerin, J., Kheddar, A., Sauques, L., Chevrot, C. & Teyssie, D. (2010). Poly(3,4-ethylenedioxythiophene)-containing semi-interpenetrating polymer networks: a versatile concept for the design of optical or mechanical electroactive devices. *Polym. Int.*, Vol. 59, No. 3, pp. 313-320, ISSN 1097-0126.

Vlad, A., Dutu, C. A., Jedrasik, P., Sodervall, U., Gohy, J. F. & Melinte, S. (2012). Vertical single nanowire devices based on conducting polymers. *Nanotechnology*, Vol. 23, No. 2, pp. 5, ISSN 0957-4484.

Wallace, G., Campbell, T. & Innis, P. (2007). Putting function into fashion: Organic conducting polymer fibres and textiles. *Fiber. Polym.*, Vol. 8, No. 2, pp. 135-142, ISSN 1229-9197.

Wang, H. L., Gao, J. B., Sansiñena, J. M. & McCarthy, P. (2002). Fabrication and characterization of polyaniline monolithic actuators based on a novel configuration: Integrally skinned asymmetric membrane. *Chem. Mater.*, Vol. 14, No. 6, pp. 2546-2552, ISSN 0897-4756.

Wilson, S. A., Jourdain, R. P. J., Zhang, Q., Dorey, R. A., Bowen, C. R., Willander, M., Wahab, Q. U., Al-hilli, S. M., Nur, O., Quandt, E., Johansson, C., Pagounis, E., Kohl, M., Matovic, J., Samel, B., van der Wijngaart, W., Jager, E. W. H., Carlsson, D., Djinovic, Z., Wegener, M., Moldovan, C., Iosub, R., Abad, E., Wendlandt, M., Rusu, C. & Persson, K. (2007). New materials for micro-scale sensors and actuators: An engineering review. *Mat. Sci. Eng. R*, Vol. 56, No. 1-6, pp. 1-129, ISSN 0927-796X.

Woosoon, Y., Joonsoo, L. & Kwang, J. K. (2007). An artificial muscle actuator for biomimetic underwater propulsors. *Bioinspir. Biomim.*, Vol. 2, No. 2, pp. S31, ISSN 1748-3190.

Wu, Y., Zhou, D., Spinks, G. M., Innis, P. C., Megill, W. M. & Wallace, G. G. (2005). TITAN: a conducting polymer based microfluidic pump. *Smart. Mater. Struct.*, Vol. 14, No. 6, pp. 1511-1516, ISSN 0964-1726.

Yang, F., Xiaobo, T. & Alici, G. (2008). Robust Adaptive Control of Conjugated Polymer Actuators. *IEEE Trans. Control Syst. Technol.*, Vol. 16, No. 4, pp. 600-612, ISSN 1063-6536.

Yao, Q., Alici, G. & Spinks, G. A. (2008). Feedback control of tri-layer polymer actuators to improve their positioning ability and speed of response. *Sens. Actuat. A-Phys*, Vol. 144, No. 1, pp. 176-184, ISSN 0924-4247.

Zainudeen, U. L., Careem, M. A. & Skaarup, S. (2008). PEDOT and PPy conducting polymer bilayer and trilayer actuators. *Sens. Actuat. B-Chem*, Vol. 134, No. 2, pp. 467-470, ISSN 0925-4005.

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