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A Stiffness Enhancement Methodology for Artificial Muscles

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***Abstract*—Electroactive conducting polymer actuators have been proposed as alternative to conventional actuators due to their extraordinary properties. This paper reports on a stiffness enhancement methodology for cantilever type conducting polymer actuators based on a suitably designed contact surface with which the actuators are in contact during operation. Finite element analysis and modeling are used to quantify the effect of the contact surface on the effective stiffness of a tri-layer cantilevered beam, which represents one-end free, the other end fixed polypyrrole (PPy) conducting polymer actuator under a uniformly distributed load. After demonstrating the feasibility of the stiffness enhancement concept, experiments were conducted to determine the stiffness of bending-type conducting polymer actuators in contact with a range (20-40mm in radius) of circular contact surfaces. The simulation and experimental results demonstrate that the stiffness of the actuators can be varied in a nonlinear fashion using a suitably profiled contact surface. The larger is the radius of the contact surface, the higher is the stiffness of the polymer actuators.**

I. INTRODUCTION

ELECTROACTIVE conducting polymers have attracted the attention of many researchers since their discovery in mid 1970s. One reason for this interest is that the electroactive polymers are considered to be alternative to conventional actuator and sensor materials due to their small electrical energy consumption, light weight and compliant properties, biocompatibility, ability to operate in air and fluidic media, insensitivity to magnetic fields and simple fabrication [1-3]. When a small electrical potential or current is applied to the polymer actuators typified by PPy and appropriately engineered, this causes an electrochemical reaction for doping and undoping the polymer layer(s) [4-5]. This follows that the polymer layer(s) show volume expansion. Consequently, electroactive polymers, as unconventional actuators, can be used for a wide range of engineering applications such as in the growing area of biomimetics. Of these applications, the PPy actuator is employed as a propulsor in a swimming device (robot fish) [1, 2]. There is a growing interest on the use of the polymer actuators in many other bio-inspired applications, [6-7]. Further, electroactive conducting polymer actuators can be employed more importantly in micro/nano robot applications in order to be used in medical operations [8-10].

The body flexural stiffness can control propulsive force, swimming speed and therefore, swimming performance [12]. The change in stiffness by a factor of two should happen during swimming in order to realize a high-performance swimming. However, the change in the stiffness of conducting polymer actuators is not easily achieved by changing the operation parameters such as input voltage. Another solution can be to form a contact surface that when the actuator bends and touches the surface, it is stiffened. The stiffness adjusting concept proposed in this study can easily be implemented on the swimming devices propelled with caudal fins, as shown in Fig. 1.

It may be argued that the stiffness of the polymer actuators or the resistance to bending can be increased by synthesizing polymer actuators with higher flexural rigidity. This is a valid argument for actuators with a constant stiffness, but this will not allow changing stiffness during operation. With this in mind, the concept put forward in this study is comprehensive, yet simple to implement and extendable to other polymer actuators. As it has been reported in the literature [1-6], one way of increasing the force output is to apply a relatively higher input voltage. However, due to the increase in the energy consumption and possible damage to the polymer structure due to over-oxidation, this cannot be a feasible solution. Therefore, we propose to develop a suitably profiled contact surface in order to stiffen the actuator.

II. OPERATION PRINCIPLES OF CONDUCTING POLYMER ACTUATORS

Conducting polymers derived from monomers such as pyrrole, thiophene or aniline have been extensively investigated for a number of years. Their electrochemical, chemical and mechanical properties provide the fundamental basis of various devices including sensors, membranes and materials for energy storage and actuators [11].

To fabricate the polypyrrole conducting polymer actuator used in this study, a series of fabrication steps was followed. First, each side of polyvinylidene fluoride (PVDF, 110 μm in thickness is a non-conductive porous layer used for electrochemical cell separator and also reserves electrolytic ions (e.g., Li.TFSI).) was coated with thin gold layer (100˚A in thickness) with sputter coating process to increase the conductivity. Second, it was immersed in a solution which contains pyrrole monomer (0.1 M), lithium triflouromethanesulfonimide ($Li^{+}TFSI^{-}$, 0.1 M) and 1 % water in propylene carbonate (PC).

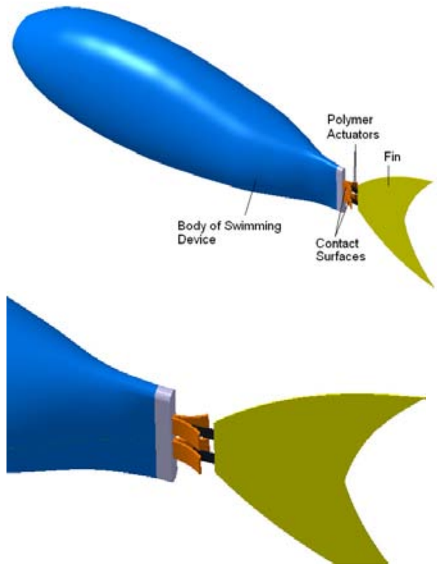
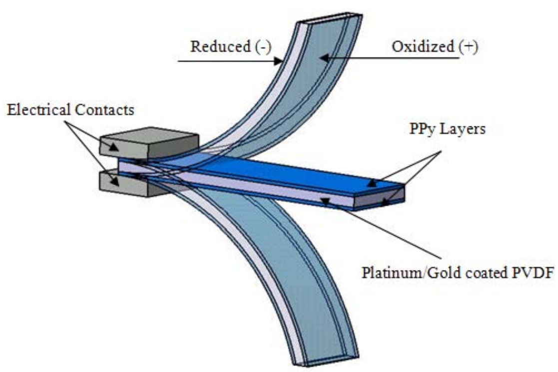


Fig. 1. Schematic representation of a suitably shaped contact surface for a swimming device propelled with a caudal fin.

The PPy layers were galvanostatically grown from the growth solution at a current density of 0.1 $mAcm^{-2}$ for 12 hours on the gold coated PVDF. This process provides approximately 30 µm thickness of polypyrrole on one side of the gold coated PVDF. Therefore, the total thickness of the conducting polymer actuator was approximately 170 µm. Five layers in the polymer actuator structure are illustrated in Fig. 2.



$$PPy^{+}(TFSI^{-}) + Li^{+} + e^{-} \leftrightarrow PPy^{\circ}(Li.TFSI^{-})$$

(doped, oxidized state) (undoped, reduced state)

Fig. 2. The operation principle of the tri-layer polypyrrole polymer actuator.

The bending mechanism relies on applying an electrical potential across the electrodes that causes an electrochemical reaction. As the electrons move from one polypyrrole layer to another through the electrolyte, one side (positively charged) expands while the other (negatively charged) contracts. Bending action and the chemical process are presented in Fig. 2 [12].

III. IMPORTANCE OF VARIABLE STIFFNESS

There are many applications, where variable stiffness is highly desirable (e.g. the hammer of a piano, the leaf spring suspension, safety stopper in lifts). With progress in artificial muscles technology, artificial muscles with variable stiffness will widen their application areas. For example, in fish swimming, the body flexural stiffness can control propulsive force, wave speed and length, and therefore the swimming speed [12].

The stiffness of a cantilevered-beam can be enhanced when it comes in contact with an external surface constraining its bending path [13]. Of course, the stiffness of a cantilevered-beam can be varied through its elastic modulus, the area moment of inertia and the beam length. The latter only can be changed during operation while the other parameters are fixed. As the beam touches the constraining surface, its length is shortened, which stiffens the cantilevered-beam in a nonlinear fashion. It may be argued that the nonlinear stiffness behaviour is not desirable, introducing complexity, to a normally, linear stiffness behaviour. This is true for cantilevered-beams with a linear deflection, where the tip deflection is less than 15% of the beam length [15]. However, the bending behaviour of conducting polymer actuators is already nonlinear. Further, depending on the application requirement, the conducting polymer actuators can be designed with discrete contact points or a continuous contact surface, as illustrated in Fig. 3.

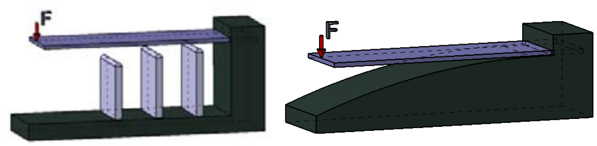


Fig. 3. A cantilevered-beam or a leaf spring in contact with discrete contact points (left) and with a continuous contact surface (right). They are two stiffness enhancement concepts.

IV. FINITE ELEMENT MODEL

We have modelled the bending behaviour of a cantilever-type composite beam with the same dimensions and the modulus of elasticity such that it produces the same deflection as the experimental conducting polymer actuator. Elasticity modulus (E) of the PPy is set to 200MPa and elasticity modulus of the PVDF is set to 117MPa [14]. We aim to show how the stiffness of a cantilevered-beam increases when it is in contact with an external surface. To this aim, the finite element analysis is accomplished for two cases which are a leaf spring deformation with and without an external contact surface with a constant radius.

A. Stiffness Analysis of a Leaf Spring with & without a Contact Surface

First, the static structural analysis is conducted, based on the assumptions which are one end of the beam is fixed, and a uniformly distributed load is applied onto the top surface of the polymer actuator, as illustrated in Fig. 4. To determine corresponding displacement results with the PPy polymer actuator experiments under a range of input voltage (0.0-1.0V), a set of simulations are conducted. Second, the distributed load generating similar deflection results is used to estimate the deflection of the beam with contact surfaces, 20, 30 and 40mm in radius.

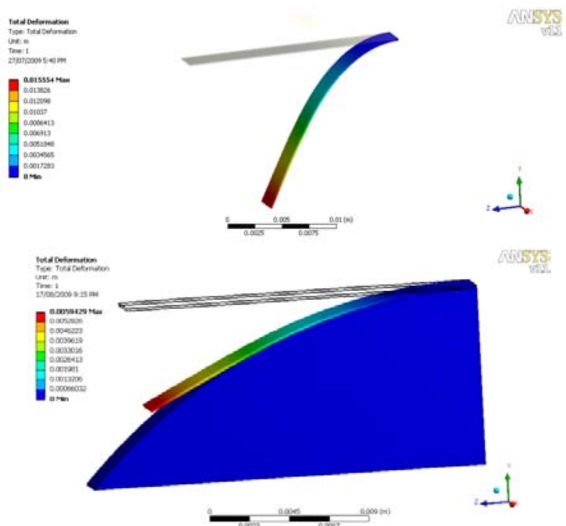


Fig. 4. The tri-layer composite beam analysis deflected structure (top) and the tri-layer beam with the contact surface, 30mm in radius (bottom).

It is found that a distributed load of 61.0583 N/m^2 on the simulated cantilever beam can generate similar displacements or tip deflections as the experimental conducting polymer actuator under 1.0 V, as shown in Fig. 5. The bending displacement of the cantilever beam in contact with a range of contact surfaces is estimated using the finite element modelling and analysis, and the results are illustrated in Fig. 6. Compared to the results in Fig. 5, the results in Fig. 6 show that the resistance to the bending, i.e. stiffness of the cantilever beam has increased significantly when it is in contact with an external surface though it is a nonlinear, stiffening effect.

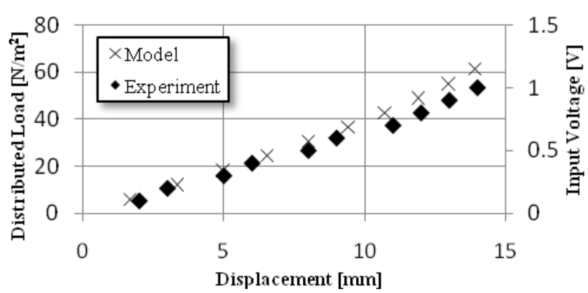


Fig. 5. Tip displacement comparison of the experimental data and the theoretical data from the finite element model.

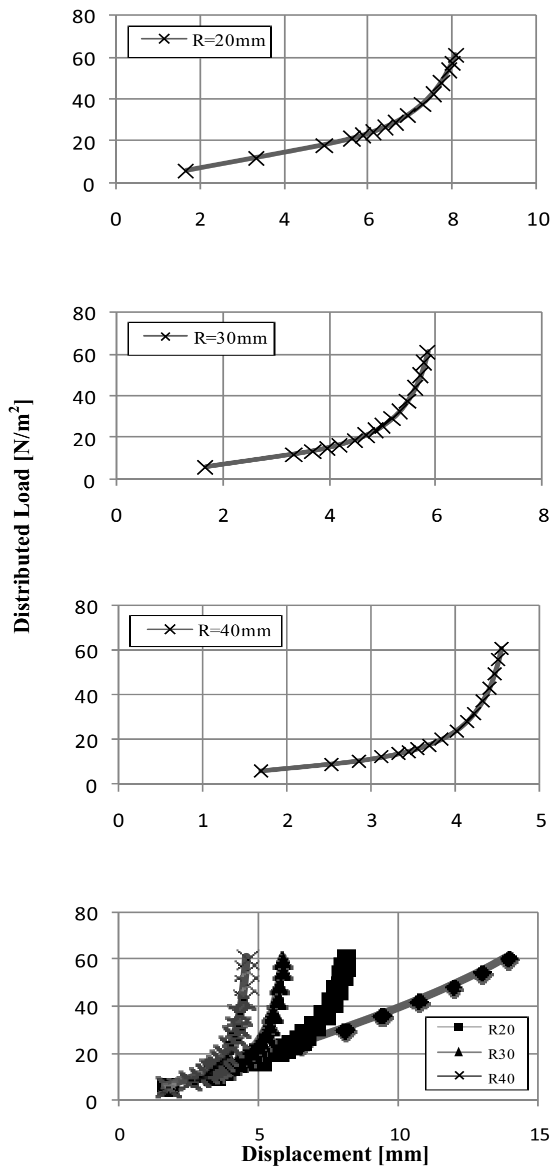


Fig. 6. The tip deflection results from the finite element model and their comparison (bottom plot).

A. *Stiffness Analysis from Energy Storage Point of View*

With reference to the operation principle of the conducting polymer actuators, the potential energy or the electric-field energy injected into the conducting polymer actuator, U, is

$$U = \frac{1}{2} Q V \tag{1}$$

where Q and V are the charge stored and V is the potential difference applied across the polymer layers, respectively. This energy can be estimated using the exemplary experimental data presented in Fig. 8, where the charge injected is the area under the current versus time curve. On the other hand, the potential energy stored due to the bending of the polymer actuators is simply

$$U = \frac{1}{2} k x^2 \quad (2)$$

where k and x are the lateral effective stiffness (assuming that the deflection in the longitudinal direction is negligibly small) and deflection of the cantilevered conducting polymer actuator, respectively. From the comparison of Eqs.1 and 2, the effective stiffness is inversely proportional to the deflection x^2, which is constrained or reduced by the contact surface.

V. EXPERIMENTAL RESULTS & DISCUSSION

Experiments were conducted for two cases;

a) conducting polymer actuators without a contact surface,

b) conducting polymer actuators in contact with three cylindrical contact surfaces with radii of 20mm, 30mm and 40mm.

Input voltage in the range of 0.1V-1.0V was applied to the cantilevered conducting polymer actuators in a square waveform form with a frequency of 0.1 Hz. The conducting polymer actuators have the dimensions of 20x3 mm with ~0.17mm thickness, the same as the composite beam considered in the finite element analysis.

A. Experimental Design and Setup

The experimental setup consists of the tri-layer conducting polymers actuator and polycarbonate contact surfaces with different constant radii. The polymer actuators were fabricated using the procedure outlined in Section 2 and then cut into the dimensions 20mm x 3 mm which are length and width of the actuator, respectively. To be able to clamp the actuator on the surface, a piece of ferromagnetic metal and a constant magnet were used. Each surface was carved and the metal piece was glued in it. Also, a wire was soldered onto each magnet and the metal piece. The experimental contact surfaces are depicted in Fig. 7.

Fig. 7. Circular contact surfaces used (20mm, 30 mm, and 40 mm in radius).

B. Blocking Force Measurement

In order to obtain stiffness variation of the conducting polymer actuators, a correlation between force and input voltage must be determined. A series of experiments were conducted to measure the blocking force of the polymer actuators under a range of input voltages.

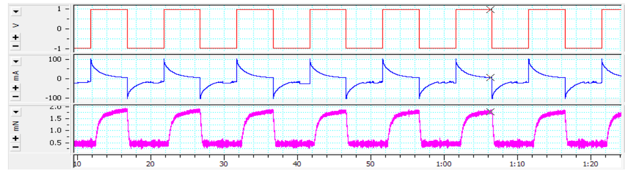


Fig. 8. The top plot, the middle plot, and the bottom plot are the input voltage, the current passed, and the blocking force, respectively, for the polymer actuator (20x3mm). The horizontal axis represents time in seconds.

The variation of the blocking force with the input voltage is depicted in Fig. 9. The conversion constant was determined to be 0.7327 mN/V for the actuator tested. This conversion number is in agreement with the previous results [15].

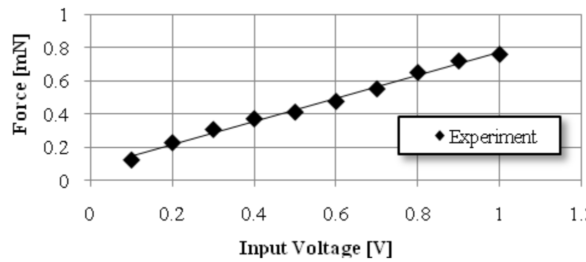


Fig. 9. Variation of the blocking force with input voltage for the polymer actuator (20x3mm).

C. Testing single beam in an open air environment

To actuate the conducting polymer actuator, e-DAQ Chart installed on PC01 was used with a function generator to apply a range of voltages. In these experiments, several conducting polymer actuators with the dimensions of 20x3mm were tested. The displacement of the beam was recorded with the PC02 which has been set up with a high resolution camera, which is a Pulnix TM-6710CL camera. The displacement data were recorded with a Labview program. Then the displacement data were measured from the actuator images. The experimental setup is illustrated in Fig. 10.

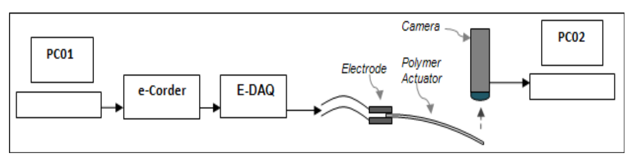


Fig. 10. Schematic of the experimental setup

Under each voltage applied, a maximum displacement was observed and the voltage which can be converted into the force with a conversion constant of which is 1.0V equals 0.7327mN per Volt. Fig. 11 shows the average values of the blocking force calculated using this conversion constant versus the displacement results without any external contact surface under a range of input voltages (0.1-1.0V).

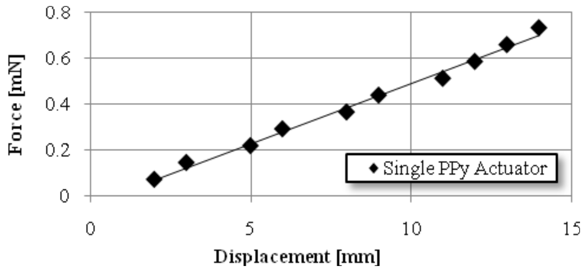


Fig. 11. Variation of the tip deflection under input force (voltage) without a contact surface.

D. Testing with continuous contact surfaces in an open air environment

Experiments were conducted for the three continuous contact surfaces, which have the radii of 20mm, 30mm and 40mm. A 20x3mm conducting polymer actuator was fixed to each contact surface.

Initial position and maximum displacement of the polymer actuator with a contact surface, 20mm in radius which was recorded by Pulnix TM-6710CL, are shown in Fig. 12. The same process was followed to measure the displacement results of the polymer actuator with the contact surfaces. The experimental results are presented in Fig. 13.

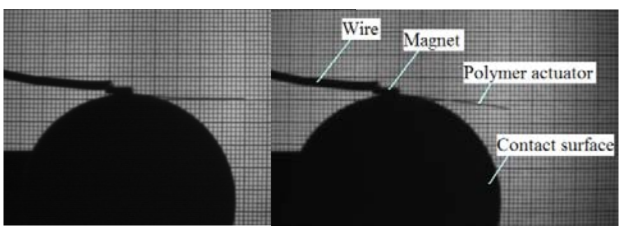


Fig. 12. Initial position (left) and maximum displacement (right) of the beam which is under 0.1V potential with the contact surface, 20mm in radius.

With reference to the numerical and experimental results depicted in Fig. 6 and 13, an external contact surface stiffens the conducting polymer actuators. The numerical and experimental results are in good agreement that as the radius of curvature of the contact surface increases, the stiffness becomes more nonlinear, showing a stiffening effect. It must be noted that the experimental stiffness results contain some uncertainty as expected from an experimental study. Some factors may be responsible for this; the actuator synthesis method may not produce exactly the same thickness actuator samples. This is true especially knowing that the actuation happens along the thickness direction, any difference in the layers' thickness will introduce some uncertainty into the experimental results. Other sources of error include the uncertainties associated with the displacement and force measurement methods used. To minimize uncertainties in the stiffness results, it is proposed to use a non-contact position measurement system, such as a laser system.

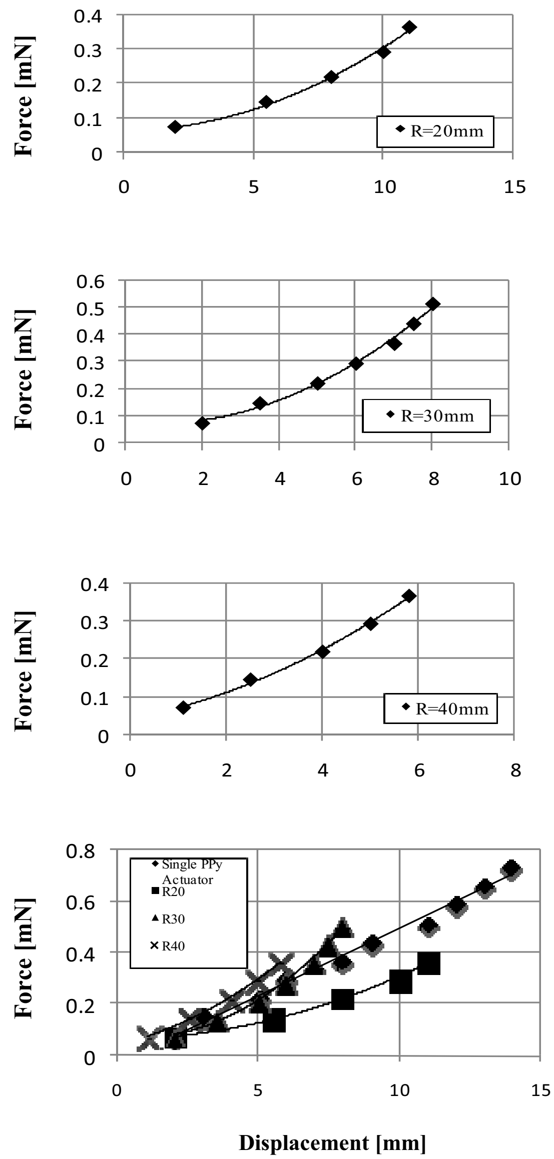


Fig. 13. Experimental tip displacement results with the contact surfaces.

VI. CONCLUSIONS & FUTURE WORK

Using the finite element modelling and analysis, we have demonstrated that a contact surface increases the stiffness of a tri-layer polymer actuator or a similar cantilevered structure when the actuator bends and begins touching the contact surface. The shape of profile of the contact surface directly affects the augmented stiffness. The numerical results show the stiffness is augmented in a nonlinear fashion when the size (e.g. radius of curvature) of the contact surface was increased.

We conducted experiments to verify the stiffness enhancement concept experimentally. The experimental results match well with the numerical results that the stiffness of tri-layer conducting polymer actuators was increased when the polymer actuator began touching the contact surface. Further, in agreement with the numerical results, it was found that the stiffness of the polymer actuator increased nonlinearly when the radius curvature of the contact surfaces increased. This follows that (i) the stiffness of the bending type artificial muscles can be adjusted to meet application requirements, and (ii) the stiffness enhancement methodology can be extended to other ionic-type conducting polymer actuators with macro and micro-sized characteristic lengths.

We plan to demonstrate this stiffness enhancement methodology for an application, e.g., a robotic swimming device like in Fig. 1. Increasing the stiffness of the propulsion elements of the swimming device during swimming will potentially increase the swimming speed as a result of a decreased drag force.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Alici G, Spinks G, Huynh N N, Sarmadi L and Minato R 2007, 'Establishment of a biomimetic device based on tri-layer polymer actuators—propulsion fins: Establishment of a biomimetic device', *J. Bioinspiration & Biomimetics,* 2 S18-30.

[2] McGovern S, Alici G, Truong V-T and Spinks G 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, 095009.

[3] Alici G and Higgins M J 2009, 'Normal stiffness calibration of microfabricated tri-layer conducting polymer actuators', *Smart Materials and Structures,* 18 065013.

[4] Alici G, Huynh N N 2006, 'Predicting force output of trilayer polymer actuators', *Sensors and Actuators*, vol.132, no.2, pp.616-25.

[5] Alici G and Huynh N N 2007, 'Performance quantification of conducting polymer actuators for real applications: A microgripping system', *IEEE/ASME Trans. Mechatronics* vol.12, no.1, pp.73–84.

[6] Madden J D W, Vandesteeg N A, Anquetil P A, Madden P G A, Takshi A, Pytel R Z, Lafontaine S R, Wieringa P A and Hunter I W 2004, 'Artificial muscle technology: Physical principles and naval prospects', *IEEE J. Ocean. Eng.,* vol.29, no.3, pp.706–28.

[7] Paquette J W and Kim K J 2004, 'Ionomeric electroactive polymer artificial muscle for naval applications', *IEEE J. Ocean. Eng.,* vol.29, no.3, pp.729–37.

[8] Sitti M 2009, 'Miniature devices: Voyage of the microrobots', *Nature,* vol.458, pp.1121-22.

[9] Zhang L, Abbott J J, Dong L, Kratochvil B E, Bell D & Nelson B J 2009, 'Artificial bacterial flagella: Fabrication and magnetic control', *Appl. Phys. Lett.* vol.94, 064107.

[10] Weibel D B, Garstecki P, Ryan D, DiLuzio W R, Mayer M, Seto J E & Whitesides G M 2005, 'Microoxen: Microorganisms to move microscale loads', *Proc. Natl Acad. Sci. USA,* vol.102, no.34, pp.11963–67.

[11] Wu Y, Alici G, Spinks G M & Wallace G G 2006, 'Fast tri-layer polypyrrole bending actuators for high speed applications', *Synthetic Metals,* vol.156, no.16-17, pp.1017–22.

[12] McHenry M J, Pell C A & Long J H 1995, 'Mechanical control of swimming speed: Stiffness and axial wave form in undulating fish models', *The Journal of Experimental Biology,* vol.198, pp.2293–2305.

[13] Timoshenko S 1958, 'Special problems in the bending of beams', *Strength of Materials Part,* vol.*2,*3rd ed., D. Van Nostrand Co., pp.69-70.

[14] John S W, Alici G & Cook C D 2010, 'Inversion-Based Feedforward Control of Polypyrrole Trilayer Bender Actuators', *IEEE/ASME Trans. Mechatronics,* vol.15, no.1, pp.149-56.

[15] Alici G 2009, 'An Effective Modeling Approach to Estimate Nonlinear Bending Behaviour of Cantilever Type Conducting Polymer Actuators', *Sensors and Actuators: B. Chemical*, vol.141, no.1, pp.284-92.