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Towards Micro and Nano Manipulation Systems: Behaviour of a Laminated Polypyrrole (PPy) Actuator Driving a Rigid Link

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Towards micro and nano manipulation systems: behaviour of a laminated polypyrrole (PPy) actuator driving a rigid link

Stephen W. John and Gursel Alici

Abstract— Conducting polymer actuators, such as Polypyrrole (PPy), incorporated into the structure of a manipulation system may be able to achieve micro and nanoscale precision, by avoiding effects such as backlash or friction. As a step towards this goal, laminated PPy actuators were varied in size and their behaviour investigated while constantly loaded by a rigid link. This behaviour has been evaluated in terms of the bending angle and force outputs of the actuator. It was found that the bending angles varied with length, but displayed unexpected trends due to the loading effects on the PPy. Force output of the actuators was also measured, with unloaded PPy producing greater force across all lengths than the near constant output of loaded PPy, attributable to the polymer and load interface.

I. INTRODUCTION

In the pursuit of functional manipulators with micro and nanoscale accuracy, it is believed that incorporating conducting polymer actuators into the structure of a device can provide a high degree of precision. This would be achieved by using the strain properties of the polymer to drive the mechanism without the need for prismatic or revolute joints, avoiding nonlinearities such as backlash or friction. Before these mechanisms can be developed, however, the effects of constant loads (such as a manipulator structure) on the conducting polymer must be understood.

Polypyrrole (PPy) belongs to a class of polymers that can conduct electricity and, if appropriately doped during manufacture, demonstrate a volume change when applied with a potential. By manipulating the shape and form of PPy, this volume change (or strain) can be harnessed to provide an actuation force.

Substantial research effort has been placed into the development of PPy conducting polymer actuators. Early generations of conducting polymer actuators produced strain only while surrounded by an electrolyte, limiting the operating environment. Later developments produced laminated actuator films, utilising a porous membrane or gel between PPy layers to contain the electrolyte allowing

operation outside of an electrolytic fluid. Laminated five-layer actuators are routinely manufactured by the Intelligent Polymer Research Institute of the University of Wollongong, consisting of a porous poly(vinylidene fluoride) (PVDF) layer coated on both sides first by platinum and then PPy.

Attempts have been made to develop mechanisms utilising the strain properties of PPy, with a number of papers presented describing the use of polypyrrole and rigid materials. These materials have included benzocyclobutene (BCB) [1, 2] or silicon [3, 4], used in micro scale devices, for applications such as manipulators capable of picking and placing micro objects. The aforementioned studies have all used a microelectromechanical based manufacturing techniques, where the mechanism is built in a number of patterning and deposition stages. These approaches are useful as they are based on well-known processes and may be performed without human intervention. Smela [5] has presented a review on a number of available techniques for manufacture with polymers at a micro scale. Mechanisms developed through this process, however, are required to be submersed in some electrolyte as there is no means for electrolyte storage. Solid polymer electrolytes [6] may have potential here if they can be appropriately deposited onto the PPy surface, but their application to bending actuators in place of PVDF may see significant reductions in mechanical strength.

The study by Jager et al. [1] examined the use of a mechanism constructed of bi-layer polypyrrole bending actuators and rigid BCB links to grasp and manoeuvre a 100 μm glass bead between gates spaced 60 μm apart. Control of the actuator movement was simple, with voltages adjusted to give an approximate position. It is proposed that, when combined with an appropriate model of the polymer and gripper, it will be possible to develop a control system capable of higher precisions – into the lower micro and nano scales. In place of the bi-layer bending actuators, laminated five-layer actuators will be used, allowing operation outside of electrolytic fluid. The polymer actuator will not only provide the movement for the device, but also a large part of the structure.

While laminated and rigid structures attached to conducting polymers have been reported on, few studies have been found in the literature that examine the effect of load on PPy, with none concerning five-layer actuators. Otero and Cortes

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[7] looked at some of the properties of a three-layer bending actuator submerged in electrolyte, while Spinks *et. al.* [8] reported on the strain response of a single film of PPy under load. This study looks to examine some of the behaviour of laminated PPy actuators while subjected to a load, as a step towards the development of a system model and ultimately a device capable of high precision movement.

II. EXPERIMENTAL CONFIGURATION

A. Actuator

Laminated five-layer actuators, as shown in Fig. 1, were used exclusively throughout these experiments, consisting of a 110 μm thick porous poly(vinylidene fluoride) (PVDF) (Millipore) membrane coated on both sides by 30 μm of polypyrrole (PPy). Prior to deposition of polymer, the PVDF was sputter coated with platinum for 20 minutes, forming a layer between 10 and 100 \AA thick. Polymerisation occurred over 12 hours, using 0.06M pyrrole monomer and 0.05 tetrabutylammonium hexafluorophosphate (TBA-PF₆) with propylene carbonate (PC) and 2%(w/w) water as solvent. The temperature was controlled between -28°C and -20°C, with a constant current density of 0.1 mA/cm². The electrolyte contained within the PVDF was 0.25M TBA-PF₆ in PC.

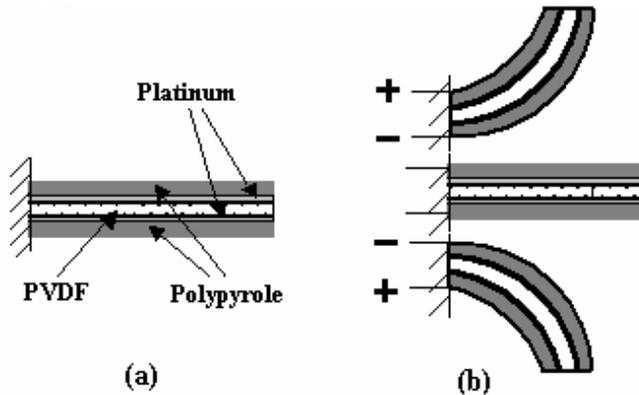


Fig. 1 Schematic representation of (a) conducting polymer actuator and (b) bending principle.

A single sheet was fabricated with approximately 60% of the PVDF covered in PPy, from which all actuators were cut to size. Where rigid links were used they were attached to the bare 40% of PVDF, otherwise the excess PVDF was trimmed away. Before the first use, all actuators were cycled 20 times to normalise the strain response [9].

Throughout all tests, the size of the actuator was modified to identify the effects of loading with relation to actuator size, selected as a proportion of the rigid link length, given in Table 1.

B. Rigid Link (Load)

To represent a potential load or a component of a future mechanism, rigid links were fabricated and attached to the

Proportion of Rigid Link Length [%]	PPy Actuator Length [mm]
100	32.0
90	29.0
80	25.5
70	22.0
60	19.0
50	16.0
40	13.0
30	09.5
20	06.5
10	03.0

Table 1: Lengths of PPy actuators used throughout the experiments, rounded to the nearest 0.5 mm. The rigid link that formed the load remained at a constant 32 mm throughout all experiments.

PPy actuators, illustrated in Fig. 2. The links were constructed individually using 4.8 mm 12K carbon fibre tow (Aerospace Composite Products) and two-part epoxy (Bostik) as a resin. Once the epoxy had set, the links were attached to the PVDF using permanent double-sided Scotch tape (3M), with 3 mm of the rigid link in contact with the PPy (see Fig. 2(c)). A number of adhesives were trialed to set the carbon fibre and adhere it to the PVDF simultaneously, including epoxy and cyanoacrylate; however, nothing has been found to be compatible with the solvent (PC) found in the electrolyte.

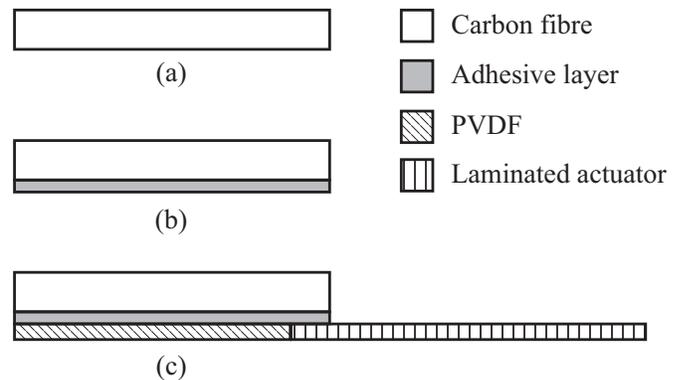


Fig. 2 Manufacturing process for actuator with load. (a) Formation of rigid link using carbon fibre and epoxy. (b) The application of the adhesive layer to the rigid link. (c) Rigid link is attached to the exposed PVDF that extends from the laminated five-layer actuator. Approximately 3 mm of the rigid link overlaps the PPy actuator to form a sound connection.

C. Bending Angle

The bending angle of an actuator was measured to characterise the range of movement possible. Where a load was attached to the PPy actuator, the bending angle achieved by the rigid link was also taken. An illustration of the bending angle is presented in Fig. 3 and Fig. 4, for the unloaded and loaded actuators, respectively.

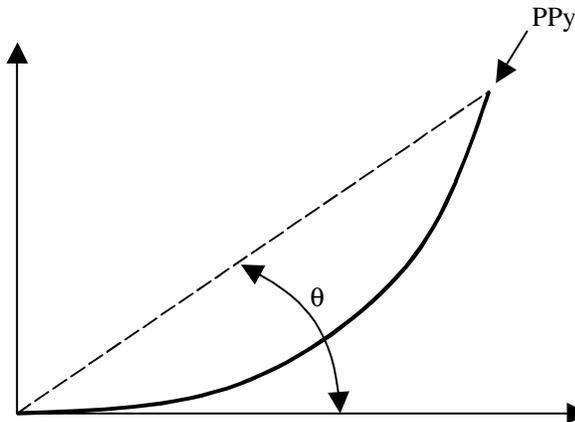


Fig. 3 Illustration of the bending angle measurement, θ , taken for unloaded PPy.

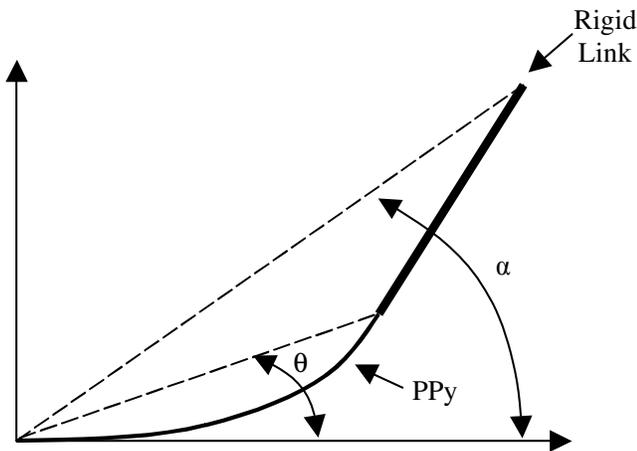


Fig. 4 Illustration of the bending angle measurements for a loaded actuator – θ for the PPy (comparable to that of unloaded PPy) and α for the angle achieved by the link.

The actuators were held horizontally by a platinum tipped clamp, and were driven by a ± 1 V, 0.1667 Hz (10 pulses per minute) square wave with 50% duty cycle. To measure the bending angle, a sheet of 1 mm graph paper was placed underneath the actuator and a digital video camera positioned above to record the movement, as given in Fig. 5.

D. Force Output

To identify the force output possible from the actuator with and without a load, a dual mode lever arm system (Aurora Scientific, model 300B) and eDAQ datalogger was utilised. The tip of the actuator or rigid link was held against the lever arm in a horizontal position, with the resulting movement converted to a force and position signal. A continuous voltage signal was applied to the actuators until full oxidation or reduction had occurred, so as to obtain the maximum force output.

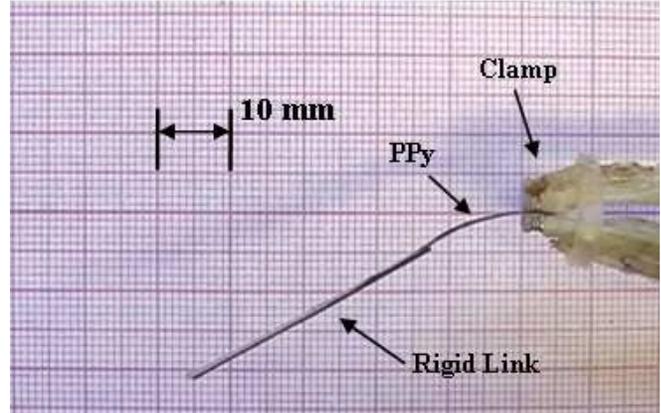


Fig. 5 Bending angle experiment as viewed from above, showing actuator, load, electrode clamp and millimetre graph paper.

III. RESULTS

A. Bending Angle

The tests were performed as described and the bending angle of the PPy was measured for six samples, three of which were loaded with a rigid link, with results shown in Fig. 6.

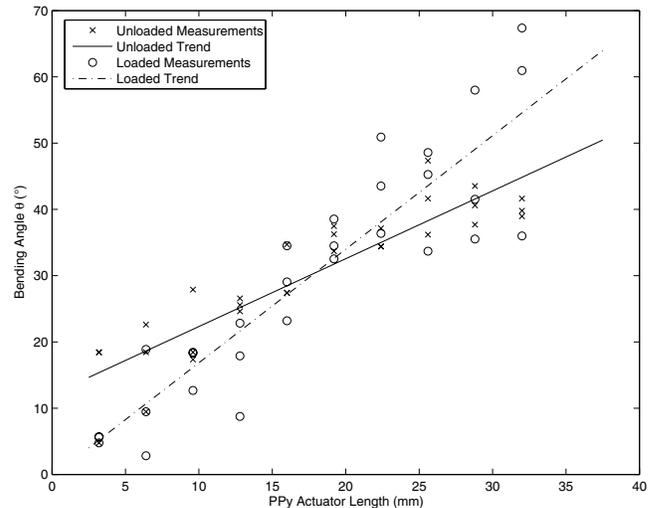


Fig. 6 PPy bending angle measurements for both loaded and unloaded actuators. Trendlines have been included – $y = 1.02x + 12.08$ and $y = 1.71x - 0.29$ for unloaded and loaded respectively.

The final bending angle, denoted by α , was also measured for the three actuators with rigid links, with results presented in Fig. 7.

B. Force Output

The six actuators used for the bending angle tests were also tested using the dual mode lever arm to identify the force output, with results shown in Fig. 8.

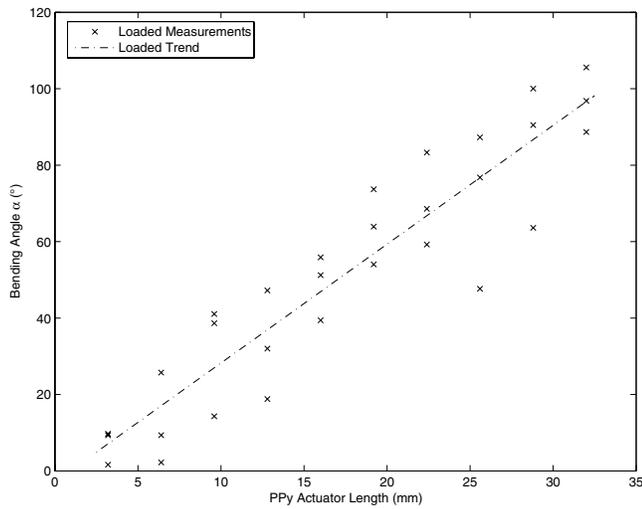


Fig. 7 Final bending angle α achieved by the rigid link. A linear trendline has been fitted ($y = 3.11x - 284$)

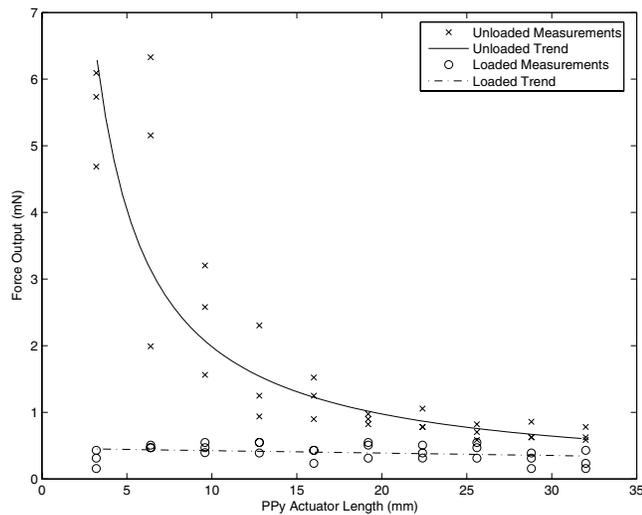


Fig. 8 Force measurements and trends for loaded and unloaded actuators. A linear trendline has been included for loaded results ($y = -0.0036x + 0.46$), and a power trendline for unloaded actuators ($y = 21.06x^{-1.03}$).

IV. DISCUSSION

A. Actuator and Construction

The PPy actuators used in this study had layers of comparable thickness (Fig. 9), producing similar motions in each possible direction of movement. Where fabrication of the actuators does not produce layers of a similar thickness, through manufacturing anomalies or otherwise, directional variations in force and bending can occur due to the unequal strain generated by the polypyrrole.

Polypyrrole actuators, when under voltage control, have been reported to exhibit a net oxidation after a number of cycles [9].

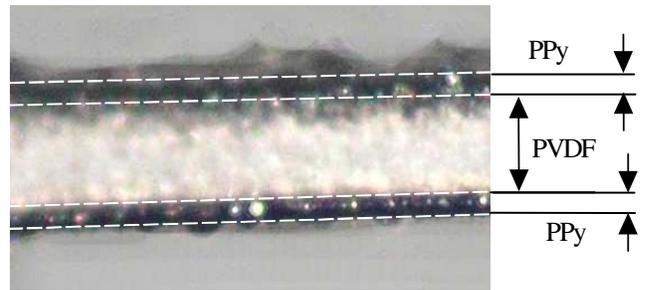


Fig. 9 Magnified image of PPy actuator, showing the centre PVDF membrane coated on either side by polypyrrole

As each sample used in this experiment was used for force and bending angle measurements over a number of different lengths, it is possible that the results reported near the end of the test (that is, at smaller actuator lengths) have been affected. As the oxidation and reduction is performed on opposing PPy layers each cycle, the overall net oxidation should be similar for both – resulting in an overall reduction in actuation capability.

Carbon fibre was selected over other materials presented in the literature, such as BCB or silicon, given the high rigidity and low weight the material affords. The amount of construction effort required is also substantially less on the macro scale when compared to actuators utilizing silicon links, with only a few steps required before completion. Measurements indicated that the adhesive, load and PVDF combination weighed approximately 0.05g each. This construction process has worked reasonably well for actuators down to 1 mm wide, but if the size of the actuators is reduced further, then some revision may be required.

B. Bending Angle

The trend shown by the loaded PPy bending angles begin well below that of the unloaded trend as would be expected; however the loaded trend displays a steeper slope than the unloaded data, eventually producing larger bending angles. This is due to the effects of the load on the PPy actuator skewing the trend; at longer lengths, the actuator was not torsionally stiff enough to properly support the actuator load, causing it to twist and distort. Furthermore, the moment generated by the load would create unequal loading strains in the top and bottom of the PPy, generating unequal volumetric strains along the PPy face and thus a twisting motion upon actuation and movement. To avoid these effects during testing, it would be possible to run the actuator while operating vertically but the additional effects of gravity would then have to be taken in account.

C. Force Output

The curve fitted to the unloaded force data, shown in Fig. 8, has a power approximately equal to -1, indicating that the force output measured is inversely proportional to length of

the actuator. The physical significance of this relationship has yet to be identified.

There is a discrepancy between the force output of the loaded and unloaded samples beyond that reasonably expected by loading alone, especially at actuator lengths smaller than 22.5 mm. Two factors may be responsible for this – distortion or bowing of the polypyrrole and a weak junction between the load and the actuator material.

At larger unloaded actuator sizes, bowing of the polypyrrole occurred, reducing the amount of force that could be applied to the lever arm. An illustration of the effect is given in Fig. 10. This explains that while the PPy in larger five-layer actuators produce greater strain than their smaller counterparts – the smaller actuators do not suffer from bowing to a similar extent, increasing the effective output.

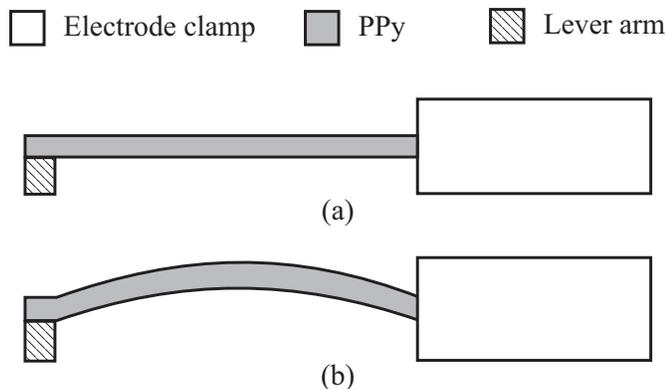


Fig. 10 Simplified illustration from above of a polypyrrole actuator (a) without and (b) with the effects of bowing. The lever arm forms part of the force measurement system. The illustration is not to scale.

In contrast to the variable force output of unloaded actuators with size, the loaded actuators exhibited almost constant force across all possible lengths. The PPy sections of the actuators here demonstrated similar bowing behaviour to the unloaded actuators. The lack of force output at smaller actuators, however, is due in part to the existence of a weak point at the junction between the start of the rigid load and the actuator material, as shown in Fig. 11.

Under maximum force output, bending occurred at this weak point, reducing the total force output in a similar manner to the bowing of the polypyrrole.

At longer PPy actuator lengths, the bowing that occurred with PPy actuators was visible; however, as the length was reduced the bowing was replaced by flexing, serving to also reduce the maximum force output. This may explain the similar trends shown in the loaded and unloaded actuators at lengths above 22.5 mm, with both loaded and unloaded PPy bowing, while the behaviour of the loaded actuator below this point is due to the flexure.

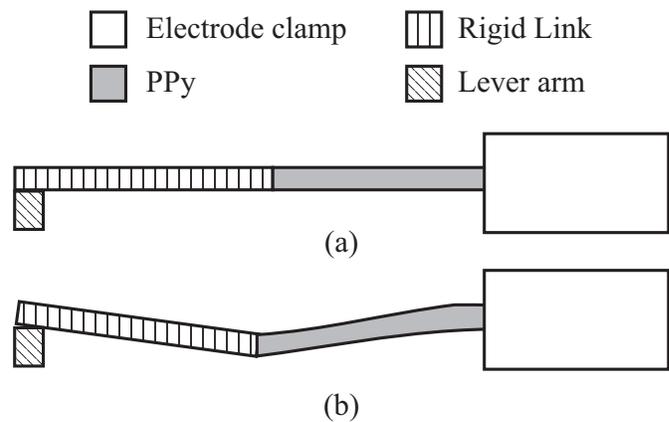


Fig. 11 Simplified illustration from above of a loaded polypyrrole actuator (a) without flex at zero force output and (b) with flex and bowing at full force output, in the direction of the lever arm. The point of flexure occurs at the junction between the PPy laminated actuator and the rigid link. The illustration is not to scale.

V. CONCLUSION

It has been proposed that high precision devices can be manufactured using polypyrrole, able to operate outside of electrolytic fluids, by combining bending five-layer actuators with an appropriate model and control system. This work forms an initial step towards the development of these devices, by examining the force and movement achievable by the system while subjected to an external load. From the results obtained, it can be seen that loading can have a large impact on the performance of bending actuators, and that a compromise between the actuation force and range of movement will be required.

Further investigation into five-layer actuator strength and construction techniques may improve on some of the limitations discussed in this report. More research is also required to fully characterise and understand the effect of further loadings, such as variable loads, before any functional manipulator system can be developed. Furthermore, for high precision manipulators, the smallest possible movement by an actuator must be identified and influential physical factors. It may then be possible to adjust the synthesis of the actuators to improve the precision. From this, it is hoped comprehensive models can be developed to predict the force and movement of a five-layer PPy actuator while loaded, and ultimately the creation a manipulator system capable of micro and nano scale precision.

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REFERENCES

- [1] E. Jager, O. Inganas, and I. Lundstrom, "Microrobots for micrometer-size objects in aqueous media: potential tools for single-cell manipulation," *Science*, vol. 288, pp. 2335-2338, 2000.
- [2] T. F. Otero and M. T. Cortes, "Controlled folding of micrometer-size structures," *Science*, vol. 268, pp. 1735-1738, 1995.
- [3] E. Jager, E. Smela, O. Inganas, and I. Lundstrom, "Polypyrrole microactuators," *Synthetic Metals*, vol. 102, pp. 1309-1310, 1999.
- [4] E. Smela, M. Kallenbach, and J. Holdenreid, "Electrochemically driven polypyrrole bilayers for moving and positioning micromachined silicon plates," *Journal of Microelectromechanical Systems*, vol. 8, pp. 373-383, 1999.
- [5] E. Smela, "Microfabrication of PPy microactuators and other conjugated polymer devices," *J. Micromech. Microeng.*, vol. 9, pp. 1-18, 1999.
- [6] T. Lewis, L. Kane-Maguire, A. Hutchinson, G. Spinks, and G. G. Wallace, "Development of an all-polymer, axial force electrochemical actuator," *Synthetic Metals*, vol. 102, pp. 1317-1318, 1999.
- [7] T. F. Otero and M. T. Cortes, "Characterization of triple layers," presented at Smart Structures and Materials 2001: Electroactive Polymer Actuators and Devices, 2001.
- [8] G. Spinks, L. Liu, G. G. Wallace, and D. Zhou, "Strain response from polypyrrole actuators under load," *Advanced Functional Materials*, vol. 12, pp. 437-440, 2002.
- [9] G. Spinks, B. Xi, D. Zhou, V.-T. Truong, and G. G. Wallace, "Enhanced control and stability of polypyrrole electromechanical actuators," *Synthetic Metals*, vol. 140, pp. 273-280, 2004.