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Tri-layer Conducting Polymer Actuators with Variable Dimensions

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ABSTRACT

The ability of conducting polymer actuators to convert electrical energy into mechanical energy is influenced by many factors ranging from the actuators physical dimensions to the chemical structure of the conducting polymer. In order to utilise these actuators to their full potential, it is necessary to explore and quantify the effect of such factors on the overall actuator performance. The aim of this study is to investigate the effect of various geometrical characteristics such as the actuator width and thickness on the performance of tri-layer polypyrrole (PPy) actuators operating in air, as opposed to their predecessors operating in an appropriate electrolyte. For a constant actuator length, the influence of the actuator width is examined for a uniform thickness geometry. Following this study, the influence of a varied thickness geometry is examined for the optimised actuator width. The performance of the actuators is quantified by examination of the force output, tip displacement, efficiency as a function of electrical power and mechanical power, and time constant for each actuator geometry. It was found that a width of 4mm gave the greatest overall performance without curling along the actuator length (which occurred with widths above 4mm). This curling phenomenon increased the rigidity of the actuator, significantly lowering the displacement for low loads. Furthermore, it was discovered that by focussing a higher thickness of PPy material in certain regions of the actuators length, greater performances in various domains could be achieved. The experimental results obtained set the foundation for us to synthesize PPy actuators with an optimised geometry, allowing their performance to reach full potential for many cutting applications.

Keywords: conducting polymer actuator, geometry optimisation, performance quantification

1. INTRODUCTION

Conducting polymer (CP) actuators are a relatively new technology with exciting characteristics that lend themselves to applications in the micro/nano technology field. The main feature of these actuators lies in their capacity to convert electrical energy into mechanical energy through an electrochemical oxidation/reduction process. Even with excitation of small voltages, ion movement is induced within the polymer that causes the volume of the polymer to expand or contract. This volume change results in an induced strain within the polymer layer, producing a mechanical displacement that for certain configurations may be characterised by a bending tip displacement or bending moment output.

Baughman R.H. [1] categorises these actuation systems into 2 categories: electrolyte storage, and electrode storage. Both of these systems work on the basic principles of ion transfer. Electrolyte storage is seen as the process where the displaced ions (or dopant salt) are stored in the electrolyte at one extreme of actuation causing a contraction of the electrode. At the other extreme, the displaced ions are stored in the electrode causing it to expand. In electrode storage, under an applied potential, the electrodes act as a cathode and an anode which either reject or attract ions (depending on their charge) and a separating electrolyte is also present to facilitate ion transport. This electromechanical cycle can be compared to the charge-discharge process of a battery and the main advantage of electrode storage actuation is the potential to minimise the actuator's weight and volume. This is possible since the amount of electrolyte required in the actuator only needs to be sufficient to provide ionic conductivity. In electrolyte storage actuation, the electrolyte conductivity is decreased during the electromechanical cycle. This does not occur in electrode storage. Electrode storage takes advantage of an out of phase dimensional change which allows for an addition in the effects of both PPy films and hence maximum actuation.

The configuration of one such polypyrrole (PPy) based actuator system consists of five layers, a porous 110μm thick electrolyte holding layer in the middle (Polyvinylidine Flouride - PVDF), a 10-100Å sputter coated layer of gold on

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each side of the PVDF to increase conductivity, and two outside layers (usually 30μm each) of electro-active polypyrrole. For this system, there are 3 states induced within the polymer structure with an applied potential [2]. The 3 states include: an oxidised electrode, a reduced electrode and a neutral electrolyte region (PVDF). The oxidised electrode takes on a positive charge and the reduced electrode possesses a negative charge. It is this charge imbalance that generates movement of ions within the electrolyte as to attempt to neutralise the charge imbalance at each electrode.

Alici G, Mui B and Cook C [3] describe how movement of ions through the structure of the actuator induces material strains due to various factors which result in actuation. The major factor is the transfer of ion volume from the reduced electrode to the oxidised electrode. The relocation of these ions causes the oxidised electrode to expand and the reduced electrode to contract. Solvent molecules accompanying moving ions also contribute to the volume transfer in the electrodes. Introduced material strains are also attributed to electrostatic forces between now displaced ions and the polymer backbone. These electrostatic forces also contribute to the expansion and contraction of the opposing electrodes. This expansion and contraction causes a mechanical strain imbalance which forces the polymer to bend in order to accommodate this imbalance, giving a deflection and force output.

It terms of measuring the performance of conducting polymer actuators, there are 2 major outputs of which previous studies are commonly concerned with. The bending displacement and the force output at the tip. Generally, the aim is to determine the optimum geometry of a PPy actuator to deliver maximum bending displacement and force outputs. This was the challenge posed by Alici G, Metz P and Spinks G M [2]. They developed a finite element mathematical model which was used to accurately predict the bending displacement and force outputs of a uniform thickness PPy actuator. Upon achieving this goal, they continued to predict the performance of 3 other varied geometries (Fig.3).

The results showed that in terms of bending angle the uniform and decreasing step geometries yielded almost identical results at approximately 16 degrees. The increasing step geometry showed a bending angle of 13 degrees while the hill geometry achieved 12 degrees of bending. The simulated force output showed that the uniform, decreasing step, increasing step and hill geometries achieved bending moments of 0.24mN.cm, 0.272mN.cm, 0.172mN.cm and 0.175mN.cm respectively. These results led to the conclusion that geometry variation should theoretically give variation in bending angle and force outputs, and the thicker the clamped end of the actuator, the higher the force output achieved. The most important outcome from this investigation was highlighting the clear advantages to geometry optimisation and identifying the need to experimentally investigate varying geometries in order to verify the theoretical results.

In addition to this, Metz P. [4] conducted a study on the influence of the thickness of both the PPy film and the PVDF membrane using a mathematical model. The first part of the simulation involved keeping the PPy film thickness constant and increasing the thickness of the passive PVDF part of the actuator. The bending displacement of the actuator decreased as the thickness of the PVDF increased. The effect of the PVDF thickness relates to the concept of increased bending stiffness. As the PVDF thickness increases, so does the overall thickness of the actuator and in turn the flexural rigidity increases. Metz also links this phenomenon to classical beam theory which describes that an increase in thickness results in a third order decrease of bending displacement. By keeping the PVDF layer thickness constant, the effect of the PPy film thickness was found to closely mimic the increasing PVDF effects, with a peak bending displacement occurring at about 40μm. The conclusion was drawn that the active PPy film thickness had a similar influence to the PVDF thickness on the overall rigidity of the actuator. One thing to note with this model is that at low PPy film thickness values (<20μm) the capacity of the PPy layer to contract and expand becomes too weak to significantly overcome the rigidity of the constant thickness PVDF layer.

The final part of the study investigated the influence of the PPy/PVDF thickness ratio on the overall bending displacement. With a fixed total thickness/length ratio and a PPy/PVDF thickness ratio varied from 0.5-2, the amount of bending displacement variation was minimal. This result led to the conclusion that it was not the proportion of active PPy that was crucial to the overall performance of the actuator but rather it was the total thickness that governed the bending capacity of the actuator. These results, while only theoretical, are extremely useful in moving towards an optimum geometry for a PPy actuator. They also highlight the major constraint of rigidity on the bending displacement, which will heavily influence the final geometry.

Experimental investigations into the effect of the deposited polymer film thickness on the bending displacement and force outputs of an actuator have also been undertaken. Sungryul Yun et. al. [5] experimented with varying film thicknesses and gained valuable results towards determining an optimum geometry of electroactive paper actuators. Experiments were conducted on 3 test samples with electroactive film thicknesses of 20µm, 30µm, and 40µm and the potential was applied over a range of frequencies. Their results showed the trend that as the thickness of the film increased the bending displacement of the actuator tip decreased at an exponential rate, the maximum tip displacements achieved for the 3 thicknesses were 4.4mm, 4.2mm, 1.5mm respectively. This sharp drop off in bending displacement is seen to be the result of an increasing bending stiffness along the actuator. In comparison to Metz's work, we can hypothesise that at thicknesses below 20µm bending displacement will decrease significantly due to the inability of the PPy film to overcome the rigidity of the PVDF layer.

There has been significant amount of research on polymer actuators and their use in various applications in the last decade [1,6-12]. Hutchison A.S., Lewis T.W., Moulton S.E., Spinks G.M., Wallace G.G. [6] and T.W., Moulton S.E., Spinks G.M., Wallace G.G. [7] looked at the effect PPy film thickness had on the force generated by the actuator. Their results showed that the force generated by the actuator decreased as the PPy film thickness increased further supporting the theory that the overall stiffness of the actuator structure plays a large role in determining the optimum geometry. Santa et al. [12] have investigated into the modeling and characterization of a muscle-like conducting polymer linear actuator operating in an electrolytic cell. It is a simple lumped parameters model whose parameters are identified using the force and the change in the length data. Based on the bending beam method, Pei and Inganas [13] developed a mathematical model of a bi-layer strip made up of a polyethylene layer with a thin gold layer on one of its surfaces, and a polypyrrole layer to evaluate in situ volume changes in the polypyrrole layer during electrochemical undoping and doping. It was concluded that the model based was effective enough to predict mass transport and phase relaxation during the undoping and the doping. Please note that this model and the model reported by Berry and Pritchet [14] to predict humidity-induced bending of polymers are for a bilayer bending-type polymer strip, which is different than tri-layer bending actuator considered in this study. Other work relevant to our study include (i) that of Lim et al [15] who predicted the displacement output of a lightweight piezo-composite actuator by drawing a thermal analogy between the piezoelectric strain and thermally induced strain, and (ii) that of Lee et al [16] who used classical beam theory to establish an equivalent bimorph beam model to predict the displacement and force outputs of an ionic polymer-metal composite actuator. The model was verified by comparing experimental force-displacement results with theoretical results based on finite element analysis.

These PPy actuators have many promising advantages including a low actuation voltage, ability to operate in air and aquatic mediums, low cost, high speed and suitability for open loop control. Drawbacks of this technology however, include their low force output and other non-linearities due to the actuation principle which is based on mass transfer.

As research continues, the range of possible applications for this type of PPy actuators is becoming more defined. An example of a possible application is in a micro/nano manipulation system where flexure joints can be used to drive rigid links to provide a controlled movement over small domains. By conducting a performance evaluation for different polymer actuator geometries, we hope to obtain information beneficial to the optimisation and improvement of these polymer actuators for applications such as micro/nano manipulation systems and biomimetic devices.

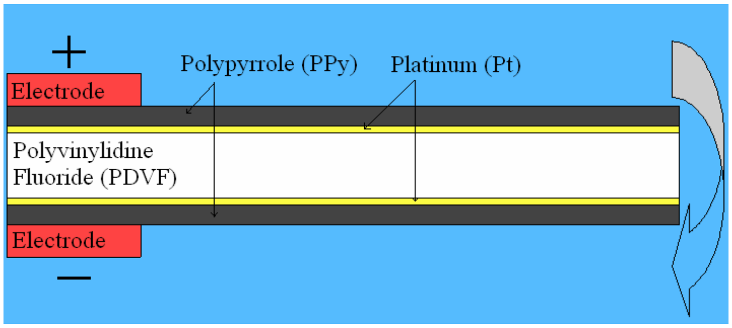

Fig. 1. PPy actuator structure.

This study has been undertaken in an attempt to build on the work of Alici, Metz and Spinks [1] who estimated the bending angle and bending moment outputs of four test geometry profiles (Fig. 1) using a mathematical finite element model developed in ANSYS. The results obtained showed that certain geometries exerted much higher bending angle and bending moment outputs compared to other geometries. With this in mind, it is clear that there is a need to experimentally verify the predicted results in order to develop a systematic approach to optimising the width and thickness geometry characteristics of PPy actuators. This study strives to set the foundation for geometry optimisation of PPy actuators which will lead to effective micro/nano manipulation system applications in the future.

2. ACTUATOR FABRICATION

Fabrication of the conducting polymer actuators was achieved by electrochemically oxidising pyrrole monomer from a solution to grow PPy layers on either side of a porous PVDF sheet (which acts as an electrical insulator and electrolyte reservoir). An *Immobilon* 110µm thick sheet of PVDF with a pore size of 0.45µm is sputter coated with a thin layer of gold (approximately 100Å) on each side. This ensures a good conductivity for electrochemical growth and an improved electron transfer along the PPy/PVDF interface. This was achieved using a sputter coating facility in the Intelligent Polymer Research Institute at the University of Wollongong.

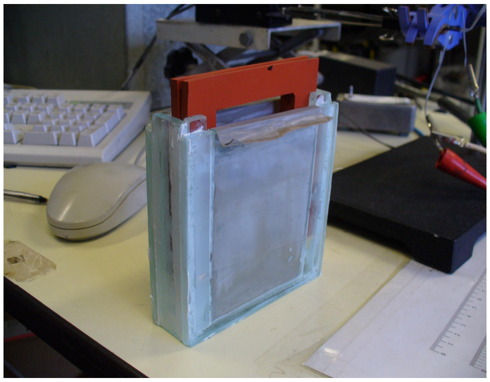

Fig. 2. Glass cell with rubber inserts and stainless steel lining.

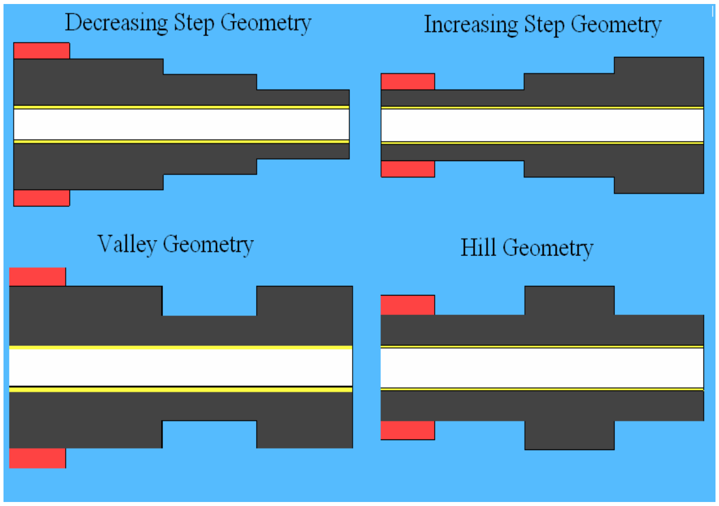

Fig. 3. Test geometry profiles.

The electropolymerisation of polypyrrole is achieved by submerging the sputter coated PVDF film in a solution of 0.1M pyrrole, 0.1M LiTFSI in Propylene Carbonate (PC) with 0.5w/w% water. The cell used for growth was constructed from glass joined together with Silastic sealant (Fig. 2). A stainless steel mesh was utilised as the counter electrode and the PVDF membrane was sandwiched between two sections of silicon rubber which have a 65mm x 50 mm rectangle cut out of the centre of each. This was used to ensure the PVDF film remained flat and centred evenly within the cell providing an even polymer deposition across the film surface. A portion of the film was left protruding out the top of the rubber for electrical connection and growth was undertaken in a freezer (-33°C) for a total period of 12hrs at current density of 1mAcm^{-2}.

In order to fabricate geometries with a varyied step thickness (Fig. 3), the growth time was altered to generate thicker and thinner sections across the actuator film. Masking tape was used to cover the portions of the PVDF film where growth time was to be shortened so that only the exposed sections of the film achieved PPy deposition. To ensure that the the gold layer was not damaged with removal of the tape, *Scotch*-Blue Painters masking tape (3M) was utilised for it's low adhesive properties.

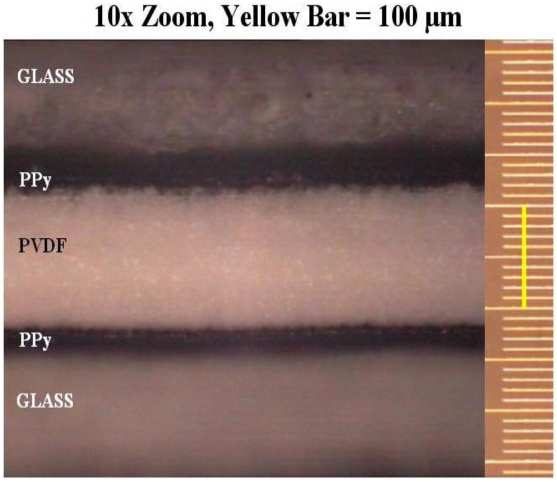

Fig. 4. Microscope image for verifying PPy layer thickness.

In the case of the increasing and decreasing step thickness samples, the initial growth time frame was 1/3 of the total growing time. At this point (after 4 hours growth), a portion of the tape was removed to expose more of the PVDF film for subsequent PPy deposition. This process was repeated one more time (at the 2/3 of the total growing time) where the remainder of the tape was removed. At completion of this process (after 12 hours), the PVDF film was completeley coated with PPy and the polymer thickness across the film was that that had resulted from 4, 8 and 12 hours growth. In the case of the hill and valley geometry profiles, the same principle was utilised with different tape placement and growing time intervals.

While the polymerisation process was controlled through a specified current density and an even spacing of the counter electrodes on each side of the PVDF, it is important to remember that electropolymerisation of PPy can be an unpredictable process and may yield results that alter the geometry and performance of the produced actuators. It is readily seen that the PPy deposition had a tendency to grow thicker at the edges of the PVDF film where diffusion related edge effects.are most prominent. The thicker edges of each of the grown actuator films were removed prior to the cutting of actuator samples for each of the different geometry experiments. The cross sectional thickness of the PPy layers was verified by viewing the actuator cross-section through a microscope fitted with a video attachment. Digital photos were taken and then compared to a scale bar as seen in Fig. 4.

3. EXPERIMENTAL SETUP AND PERFORMANCE INDICATORS

The experimental setup used to test the actuator geometries is seen in Fig. 5. A dual mode force lever arm system (Aurora Scientific) is utilised to measure the force and displacement capabilities of the actuators. An EA121 potentiostat (*e*DAQ) was used to apply a driving potential to the actuators of varied geometries. The applied voltage, and the resultant current, force and displacement signals were interfaced with an 8 channel 821 *e*CORDER (*e*DAQ) and were recorded using *Chart* software (*e*DAQ). The dual mode force lever arm works by applying an operator set resistive torque to the lever arm axle. When a force is applied to the tip of the lever arm via a PPy actuator (Fig. 6), the device outputs a voltage signal that is proportional to the experienced force. No movement with the lever arm is achieved until the applied force overcomes the set resistive torque of the lever arm, after which the displacement output may be determined from a second proportional voltage signal. When the lever arm is not deflected by the actuator then the maximum force recorded is defined as the maximum force output the actuator is capable of generating. In this way, a variety of different loads or blocking forces can be set on the actuator movement for calculation of such factors as actuator work output and efficiency.

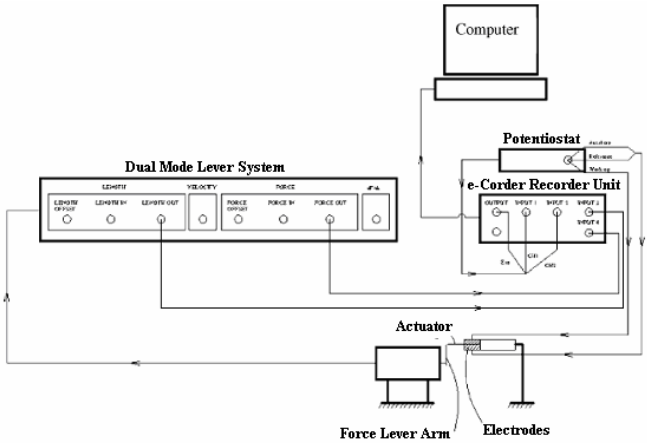

Fig. 5. Experimental setup.

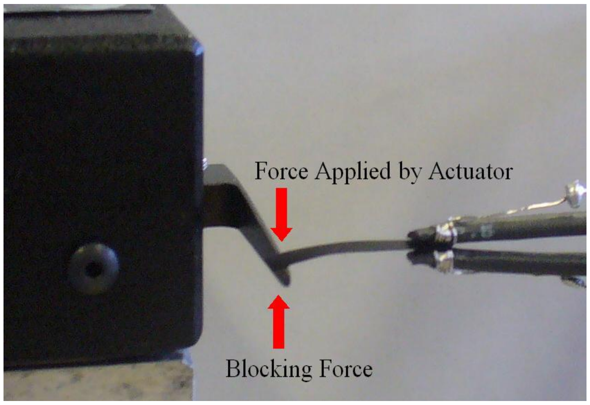

Fig. 6. Actuator force application.

The actuator to be tested was placed in an electrode clamp and the lever arm was setup in place where the tip of the actuator was resting on the tip of the lever arm. A constant length of 15mm from the electrode clamp edge to the end of the actuator was used for the duration of tests.

A square wave with +/-1V peaks was selected for the input voltage to drive actuation. The duty cycle of the square wave was defined as the ratio of the period of time at +1V (force application) to the total time for one complete +/-1V square wave cycle. This had to be set to allow for near steady state limits to be reached for each actuator tested, where steady state was defined as when the current signal had decayed to zero, and displacement had reached a plateau.

The duty cycle was set to 60% with on/off periods of 15/10 seconds respectively. The reason that the duty cycle was not set at 50% is that with a duty cycle of 50% during the -1V period the actuator removes itself from contact with the lever arm and under zero load, curls upwards and eventually back on itself. A duty cycle of 60% with a period of 25 seconds allowed for just enough time for the actuator to reach steady state force and displacement in the forward +1V cycle and zero force on the backward -1V cycle. Each actuation cycle at any given force was repeated a minimum of 5 times and averages were taken to ensure accuracy with results.

The force, displacement, voltage and current data that was recorded for each actuation cycle allowed us to generate a range of performance indicators used to evaluate each actuator geometry. These included:

- Displacement vs. Force Curve: Allows for the tip displacement achieved by each actuator to be observed over the entire range of blocking forces.
- Maximum Force Output: The highest force output achieved at the tip of each actuator geometry.
- Input Power: Average power consumed by each actuator geometry over a cycle. Calculated by $P_{IN}(t) = V(t) \cdot I(t)$
- Efficiency: The ratio of output power generated to the input power consumed over a cycle. Calculated by $\eta(t) = \dfrac{P_{OUT}(t)}{P_{IN}(t)}$
- Time Constant: Indicates how fast the each actuator geometry responds to a change in input conditions. Defined as when the current response to a step voltage input decays to 36.8% of its initial value. After 5 time constants, the actuator has reached steady state and the current is equal to 0, a smaller time constant represents a faster actuator.

A typical batch data obtained from a series of actuation cycles, including calculated data such as input/output power and efficiency can be seen in Fig. 7.

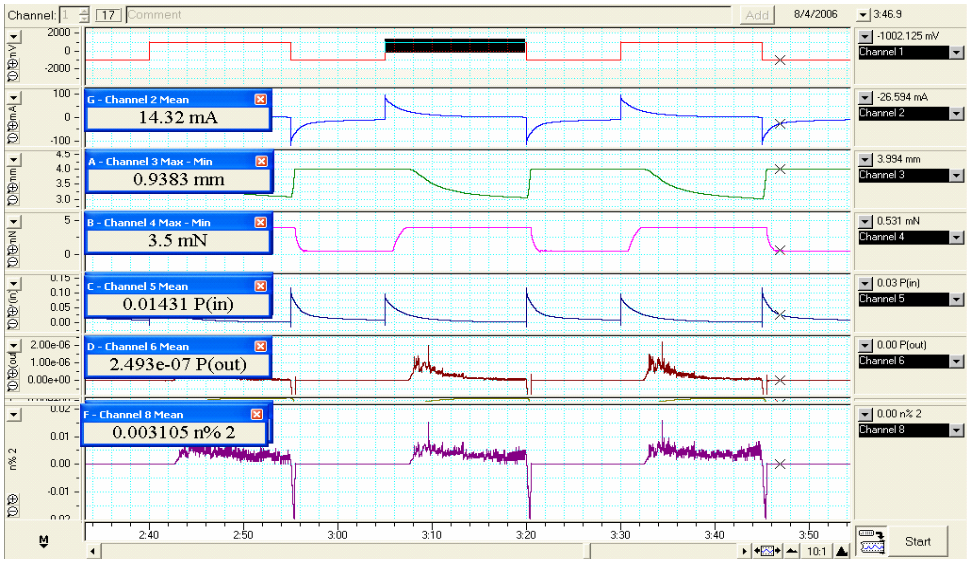

Fig. 7. Typical recorded actuation data.

4. INFLUENCE OF WIDTH ON ACTUATION PERFORMANCE

A performance evaluation of PPy actuators with a varied width was undertaken. For the different widths, the actuator length and the free bending portion of actuator was kept at a constant 20mm and 15mm respectively, (5mm was allowed for electrode connections). The thickness of PPy on either side of the PVDF film was kept at approximately 30µm. Experimentation was undertaken on a range of widths from 2 to 9mm and the performance indicators described previously were obtained for each width geometry. To ensure a uniform thickness and composition of PPy between each test all of the actuators used for the width evaluation were cut from the same film. The results of the varying actuator width tests can be seen in Fig. 8.

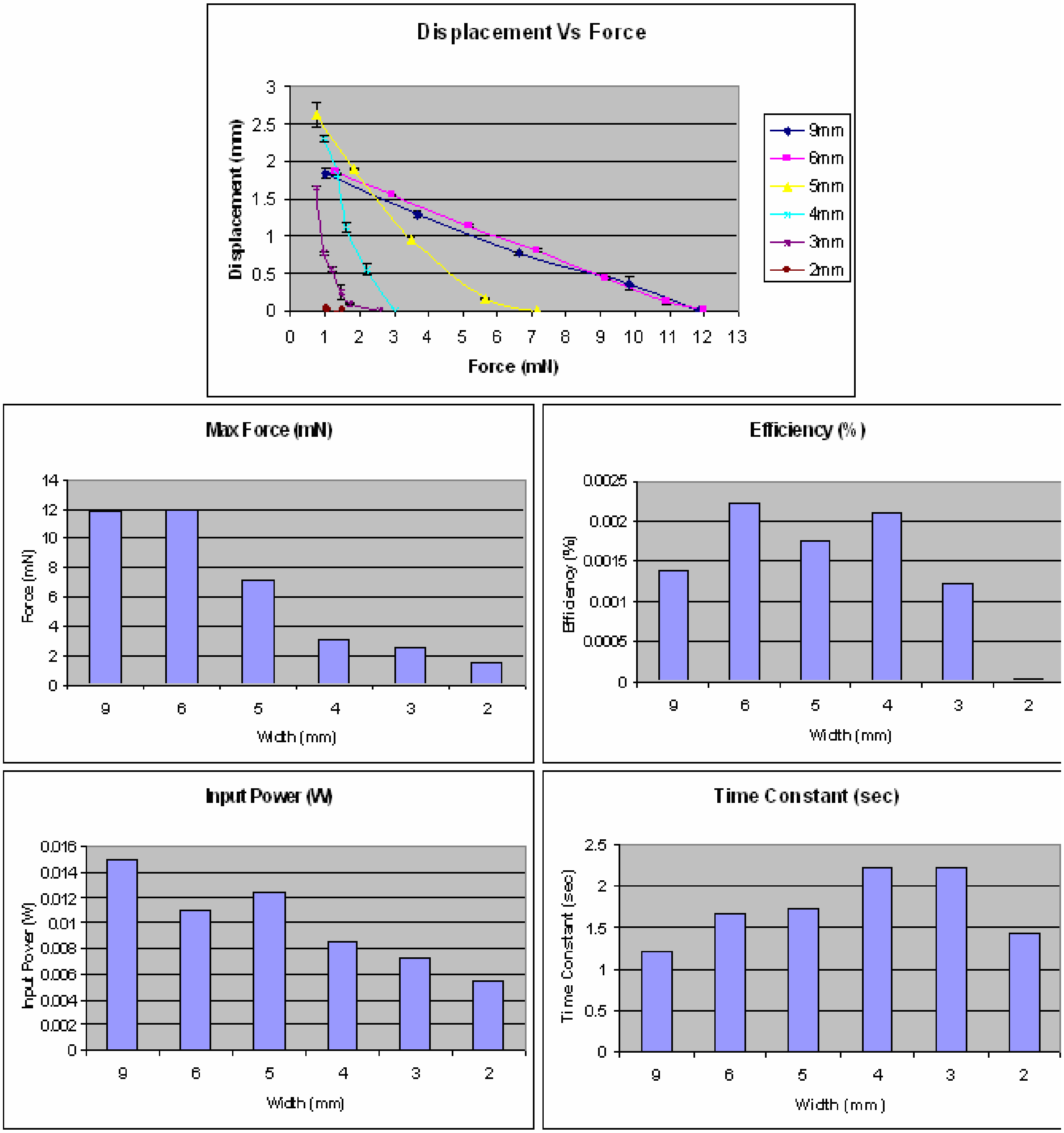

Fig. 8. Width test results.

The results of Fig. 8 show a clear influence of the actuator width on the overall performance. As the width of the actuator increases, so does the amount of electro active material (PPy) present in the structure, and the overall structural rigidity of the actuator. Since the electro active material is the mechanism for movement, an increase in the PPy actuator width results in an increase in actuator force output. On the other hand, as the structural rigidity increases the actuator becomes more resistant to bending and a reduction in the maximum displacement for low loads was seen. These results clearly show that there is a trade-off between force and displacement and an optimisation is necessary in order to maximise the actuators performance characteristics for certain applications.

Fig. 9. Curling along the actuator.

For widths of 5mm and higher, a curling type phenomenon occurred along the actuator length (Fig.9). This process increased the structural rigidity of the actuator and therefore hindered its ability to bend. As such, actuators of larger widths showed significantly smaller displacements under low loads. This was seen as a behaviour which would be undesirable in many actuator applications. For an actuator length of 15mm, a width of 4mm was taken as the optimum geometry to yield the maximum force and displacement with elimination of any curling response.

The understanding achieved of how a varied width affects each performance indicator individually is extremely valuable in the practical application of conducting polymer actuators. The fabrication of each actuator could be altered to obtain a certain geometry actuator based on the characteristics required for a given purpose. For example, in a gripper application [2] where actuators are required with a large output force and efficiency, an educated decision could be made in determining the optimum width of the actuator for the most effective operation of the gripper.

4. MATHEMATICAL MODELLING

A computer model was developed in an attempt to predict the force and bending relationships for actuators with a varied thickness geometry. Data from the varied width experiments was used to verify the model for uniform thickness geometry, and from this the effect of a varied thickness geometry was modelled using ANSYS software.

In order to achieve a conducting polymer bending actuator model capable of predicting the maximum force output across a range of widths, it is important to first understand the operation principles of the actuators. As discussed previously, actuation is achieved through an oxidation and reduction process which converts electrical energy into mechanical energy. The expansion and contraction of the PPy layers which causes actuation is a result of movement of ions through the actuator structure causing a volume change and subsequent expansion and contraction forces. While the ANSYS software is a powerful analysis tool for simulation, it is not capable of modelling the movement of ions through a structure. With this understanding, it is necessary to determine another method of simulating these expansion and contraction forces. A useful capability of the ANSYS software is the ability to simulate coupled thermal-structural effects, allowing for relationships between the real strain induced in the PPy layers due to ion flow to be simulated with an applied thermal strain. In ANSYS, when a temperature gradient is applied to a material with certain material properties, expansion and contraction occurs. This capability was utilised to mimic the volume change in the PPy layers resulting in a bending phenomenon and output force. Previous studies such as Alici G, Metz P and Spinks G M [1] have utilised this analogy to develop a finite element model, verifying the capability of this approach.

In the ANSYS environment, there are three parameters which govern the behaviour of the modelled actuator using the coupled thermal-structural approach, these are:

- Difference in temperature (ΔT): The temperatures applied to the PPy layers act as the input of the system (replacing voltage). The difference in temperature between the PPy layers mimics an applied potential and drives the simulated expansion and contraction forces.
- Coefficient of Thermal Expansion (α): Governs the tendency of the PPy layers to expand when heated (and contract when cooled).
- Modulus of Elasticity or Young's Modulus (E): A mathematical description of a materials tendency to be deformed when a force is applied to it.

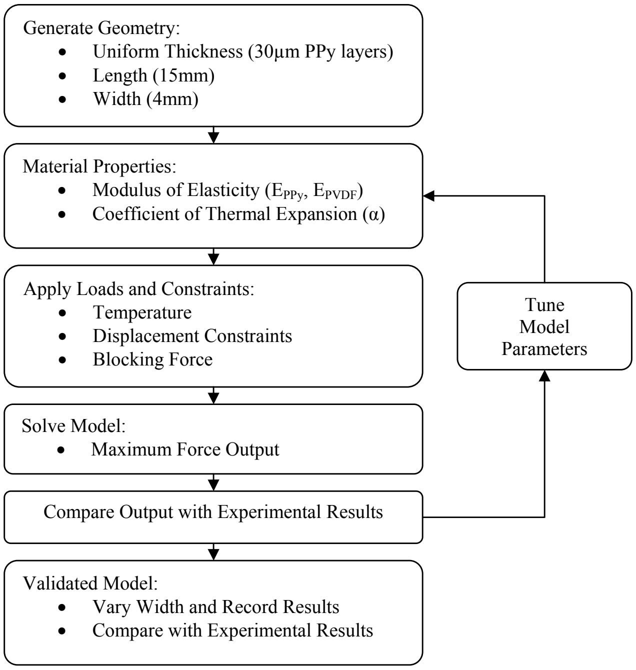

Fig. 10. Finite element modelling procedure.

Since there was a high degree of curling present in actuators with widths above 5mm, the model was tuned to replicate the maximum force output of the 4mm wide actuator using the process seen in Figure 10. Replicating the 4mm wide actuators maximum force output was achieved by setting the difference in temperature to 1^{o}F to represent a 1V potential applied to the actuator and tuning the coefficient of thermal expansion and modulus of elasticity until the experimentally obtained maximum force output was achieved. From this, the width of the actuator was varied to see if the trend follows the experimentally obtained results.

Upon observation of the recorded outputs (Fig. 11.), the experimental and simulated results were a good fit over the range of 2mm to 5mm actuator widths.

In terms of the actuator widths above 5mm, the simulated ANSYS results continue to increase as the width increases. In the ANSYS model environment, the curling effect seen experimentally occurs on a much smaller scale and could not be replicated to the same extent. With the absence of the beam-stiffening curling effect, the force output in the computer model continues to increase with width.

The validated model for low actuator widths was then used to predict the performance of the actuator geometries seen in Fig. 2. The predicted performance of 4mm wide actuators with a varied thickness geometries shows a variation in the maximum force output (Figure 12). This result shows that not only does the volume of electro active material influence the force output of the actuator but also the location of the material on the actuators structure. These predicted responses were then confirmed experimentally.

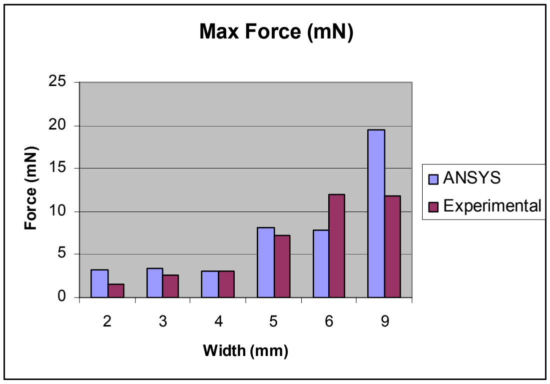

Fig. 11. Maximum force output
(Simulation (ANSYS) vs. Experimental).

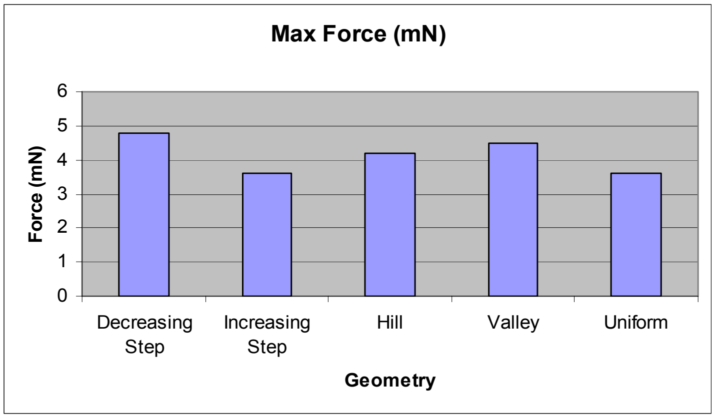

Fig. 12. ANSYS performance predictions.

5. INFLUENCE OF GEOMETRY PROFILE ON ACTUATION PERFORMANCE

In order to conduct a meaningful geometry performance evaluation, it was first necessary to obtain a set of actuator samples which have defined geometry profiles. If the dimensions of the actuators could not be quantified, the results of the study would be meaningless as there is no basis for comparison between performance indicators. By placing masking tape across certain regions of the sputter coated PVDF layer during growth, the actuator geometry profiles shown in Fig. 3 were synthesised. Again the length of the actuators tested was kept constant at 15mm (20mm total with 5mm bound by the electrode clamp) and the width of the actuators was also kept constant at 4mm. The growing time for each step thickness was varied to obtain a constant volume of PPy material throughout all of the geometry profiles. Upon inspection of the PPy layer thicknesses under the microscope, it was seen that this aim is achieved to a high degree of accuracy. The results of these varying geometry profile tests can be seen in Fig. 13.

By undertaking a performance evaluation on the various actuator profiles, a greater understanding was achieved of how the PPy layer thickness in various regions along the actuator influences the actuator response. From examination of the results of Fig.13, it is clear that the variation of geometry characteristics has a substantial influence on the performance of a conducting polymer actuator. Most notably it may be seen that by focussing the electro active PPy material on the tip and base ends of the actuator, the force and displacement outputs of the actuator are improved. The displacements seen under load for the valley geometry were also seen to show a greater than 50% improvement on the uniform geometry actuator and up to 500% improvement on all other geometries. The importance of an equal balance of PPy material at both ends of the actuator was also discovered in terms of the efficiency rating. Efficiencies for the valley geometry were similar to what was observed for a uniform geometry and were up to 4 times higher than all other geometries investigated.

In terms of the time constant of each actuator geometry, we found that the response time was influenced by the thickness of the PPy material at the point of electrical contact (actuator base). A thinner PPy layer at the base end (such as the increasing step and hill geometries seen in Fig. 3, results in a faster response time, most likely due to a faster propagation of charge through to the conducting platinum layer.

An understanding of how these geometry variations influence the performance of conducting polymer actuators allows us to optimise the fabrication process. In practice, this is a valuable tool as the most effective geometry profile actuators can be fabricated and implemented into a physical application with the highest possible performance.

In terms of overall performance, we can conclude that improvements in force and displacement output over a uniform geometry actuator may be obtained for actuators with a valley geometry. However, this is at the expense of a loss in actuator speed.

6. SUMMARY AND CONCLUSION

Conducting polymer actuators are an important new technology which represents the next generation of actuation in micro/nano scale applications. Their ability to convert electrical energy into mechanical energy via an oxidation and reduction process makes them very unique in their operation, and gives them a broad scope of possible uses in cutting edge technologies. The volume expansion and contraction induced in the actuator's structure upon an applied potential, results in a bending deformation and force output. These actuators have many advantages which add further weight to their prospective value in future applications. With this in mind, it is clear that continued study towards further developing these conducting polymer actuators is an important endeavour.

A study undertaken by Alici, Metz and Spinks [1] predicted the performance of actuators with varying thicknesses along their longitudinal axes using a lumped parameter finite element model. The results obtained suggested that actuators with certain geometry profiles achieved higher levels of performance compared to others, highlighting the need for experimental testing of this predicted result. The aim of this study was to experimentally evaluate and quantify the performance of actuators with varied geometry characteristics, such as width and thickness. This was carried out with the goal of setting the foundation for optimising the geometry of the actuators, allowing their performance to reach full potential.

In terms of quantifying the performance of the actuators, it is important to clearly define performance indicators in order to allow direct comparisons between different actuator geometries. The set of performance indications that are employed consisted of the maximum force output, displacement vs. force output, efficiency and response time (or time constant) of the actuators. In addition to this, a method for determining the thickness of PPy material deposited along the actuators' length was also defined to allow a verification of the actuators geometry.

Experimental evaluation of actuators with varying widths (and uniform thickness) highlighted the fact that the geometry characteristics of the actuators greatly influence their overall performance. It was seen that for a constant actuator length, the maximum force and displacement of the actuator increased as the width of the actuator was increased from 2 to 5mm. It was found however, that the free displacement or displacement under small loads was lowered for actuators with a width of 6mm or greater. For the 15mm long actuators and for geometries that have a width of 5mm or greater, it was seen that a curling at the edges along the length of the actuator occurred. It was believed that this had the effect of significantly increasing the structural rigidity of the actuator along the bending axis and as such, significantly higher force outputs were seen with lowered displacements. The optimum actuator width that did not encounter this curling phenomenon was found to be 4mm wide.

Significant changes in the actuator performance were also found by altering the thickness geometry profiles. For a constant length (15mm) and width (4mm) actuators were fabricated with varied step thicknesses of deposited PPy along the length. It was found that by accumulating an equivalent thickness of electro active material at the tip and base regions of the actuator, the force, displacement and efficiency outputs of the actuator were maximised. Geometry profiles with a thinner layer of PPy at the clamped end of the actuator resulted in a faster response time to changes in input conditions.

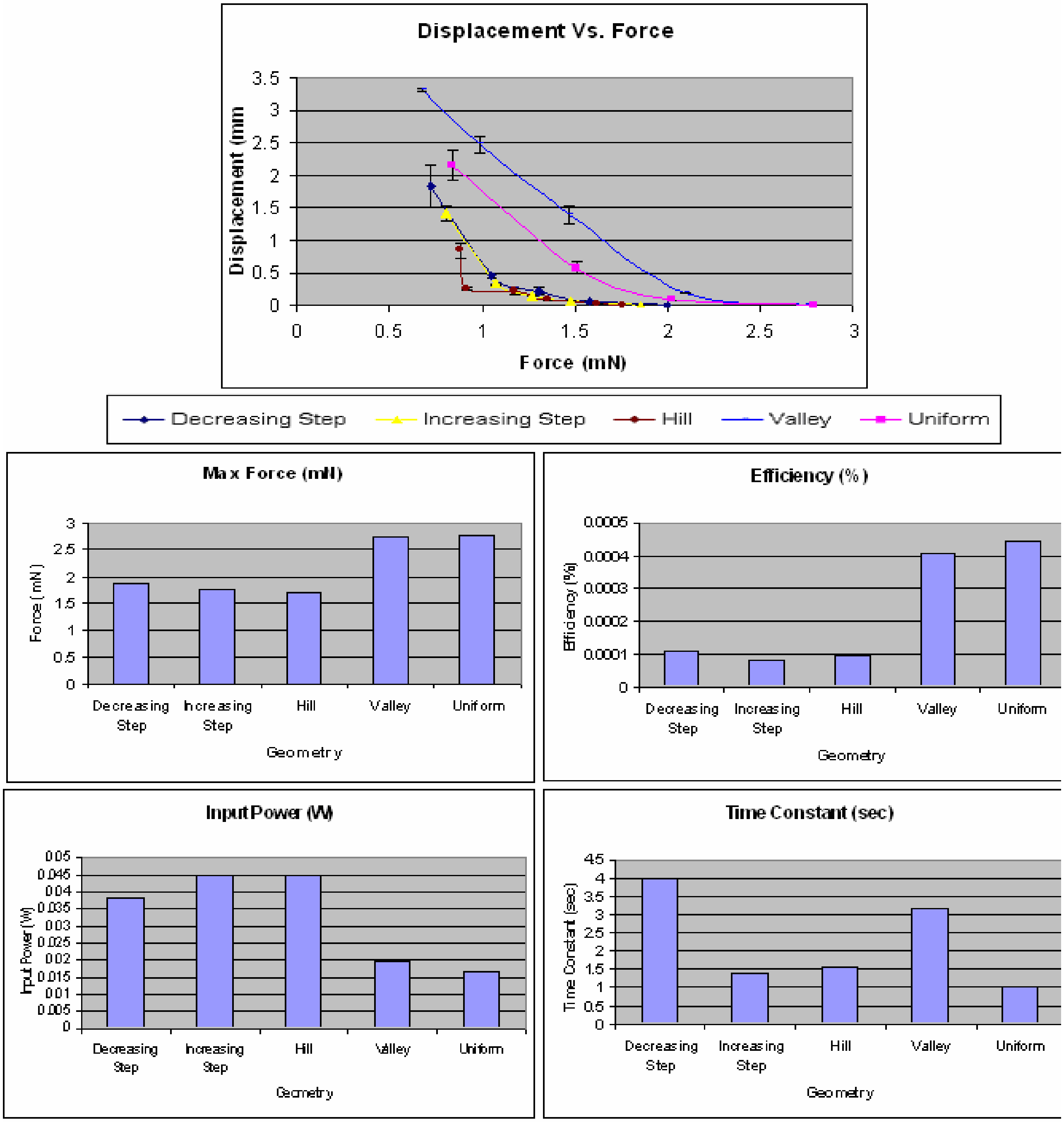

Fig. 13. Geometry profile test results.

The actuator that provided the largest displacements under different loads was that with the valley geometry, which had a greater than 50% improvement on the uniform geometry actuator under load. Although this actuator had a slower response time to the uniform geometry, the improvements in force output are significant and may find use in certain applications.

This study has been set up to generate an understanding that allows us to determine and fabricate actuator geometries based on a set of desired performance parameters. The aim of this work was to act as a guide to synthesising actuator geometries in order to reach an optimised performance for desired applications and should set a foundation for future work towards the common goal of optimising the performance of conducting polymer actuators.

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