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A Bio-Inspired Robotic Locomotion System based on Conducting Polymer Actuators

Gursel Alici, Daniel Gunderson

Abstract— **This paper presents the conceptual design and testing of a bio-inspired locomotion system activated through ionic-type conducting polymer actuators, which can operate both in dry and wet environments. The locomotion system is proposed for a mini autonomous crawling device for applications typified by pipe inspection, search, inspection and data gathering in confined spaces, which require mini-robotic systems. The locomotion system is based on the cilia, which has a simple planar bending motion. This type of motion can be provided by bending-type polymer actuators (one-end fixed and the other-end free cantilever beam). The actuators mounted on a printed circuit board and powered according to a gait design similar to the motion of biological cilia create the legged locomotion system. As the actuators require a low electric power and have a small foot-print (no sophisticated electronics and any transmission mechanisms), they are especially suitable to establish wireless autonomous mini-robotic systems. The design methodology presented in this paper is offered as a guide to establish functional devices based on bio-inspiration and conducting polymer actuators. The successful testing of the propulsion concept in the prototype demonstrates that conducting polymer actuators, when engineered properly, can be used to build functional devices.**

I. INTRODUCTION

Conducting polymer actuators based on pyrrole, thiophene or aniline have been attracting the attention of the researchers in the past decade due to their beneficial features including low power consumption, inherently compliant structure, light weight, simple construction, simple operation principle not requiring advanced electronics, insensitivity to a magnetic field, and noiseless operation. These are known as electroactive polymer actuators or artificial muscles with an operation principle based on the transfer of the ions in and out of the active conducting polymer layers [1-6]. One disadvantage of these ionic-polymer actuators is that they had to operate in a certain aqueous medium consisting of the electrolyte consisting of a salt and a solvent. This has negatively impacted on their practical applications. However, we have synthesized dry-type polymer actuators, which can operate in any aqueous media and in air. The polymer actuators used in this study are based on dry-type polymer actuators. After understanding their dynamic and static behaviours and developing mathematical models for their performance optimization and control system design successfully [5, 6], we have been motivated to establish functional devices, ranging from a swimming device to a mini-crawling device, based on the polymer actuators [7].

In this study, we present our investigation into the establishment of a legged locomotion system based on the cilia motion and bending type conducting polymers. As the force output of the actuators is limited and highly depends on the actuators dimensions, the established locomotion system is used as an inverted system like a conveyor system to test the locomotion concept and the actuation gait activated through ionic type conducting polymer actuators based on polypyrrole (PPy). The experimental results demonstrate the movement of the actuators can be controlled synchronously to push a light-weight object forward. It is our current research effort to improve the force output of the actuators and test the prototype as a mini-autonomous crawling device in a confined space.

II. CONDUCTING POLYMER ACTUATORS: SYNTHESIS AND OPERATION PRINCIPLE

The structure of the bending-type polymer actuators in this study is depicted in Figure 1a. It consists of three main layers: two outer PPy layers that are the active components and an inner porous separator of poly(vinylidene fluoride) (PVDF) that holds the liquid electrolyte, and two thin, porous gold layers with negligible thickness. This composite structure exhibits a simple bending motion like a bilayer cantilever.

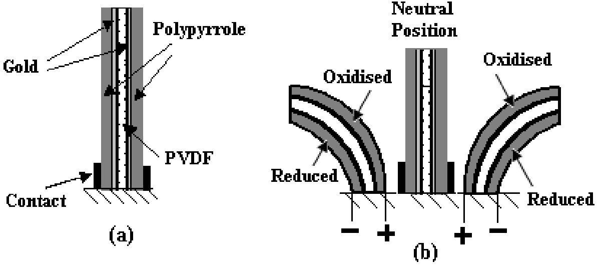

Figure 1: (a) Schematic structure of the PPy tri-layer actuator, and (b) Schematic representation of the bending principle.

The first step in the fabrication of the trilayer structure is the sputter coating of gold particles (a thickness ranging

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between 10 and 100 °A) on both sides of a PVDF sheet. The PDVF is a commercially available filter membrane with a pore size of 0.45 µm and the nominal thickness of 110 µm (Millipore). The coated layers of gold serve to provide a conductive surface on which the PPy electrodes can be electrochemically deposited. Propylene carbonate (PC, Aldrich), lithium triflouromethanesulfonimide ($Li^{+}TFSI^{-}$, 3M) were used as received. The second step is to galvanostatically grow the polypyrrole layers on the gold coated PVDF at a current density of 0.1 $mAcm^{-2}$ for 12 h from the growth solution. The solution contains 0.1M LiTFSI, 0.1M Pyrrole monomer and 1% water in PC, stirred and degassed with N_2 for 15 minutes. With this growing time, the thickness of the polymer layers was approximately 30 µm, making overall thickness 170 µm. The synthesized PPy is doped with the $TFSI^{-}$ ion during the polymerisation. The bending actuator with the desired length and width is cut from the bulk sheet. The other details about the synthesis of the polymer actuators are presented in [8].

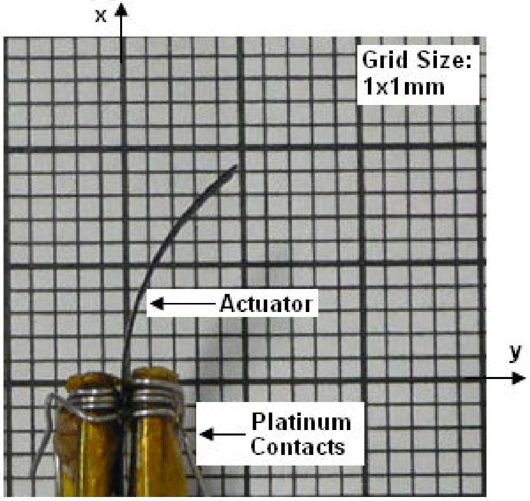


Figure 2: configuration of the polymer actuator under 0.5V during the bending displacement measurement.

With the electrolyte stored in the cell separator, the trilayer structure forms an electrochemical cell. When a potential difference or current is passed between the polymer (PPy) electrodes via the contacts, the whole structure is charged like a battery: at the positively charged electrode the PPy layer is oxidised, while the negatively charged PPy is reduced. To maintain charge neutrality within the PPy layers, $TFSI^{-}$ anions will move from the electrolyte into the positively charged polymer (PPy) electrode and hence cause a volume expansion. While this is happening in the positive electrode/anode, the anions ($TFSI^{-}$) will leave the negatively charged electrode as reduction of the PPy causes it to become uncharged and a volume contraction occurs. The overall result is that the cantilevered structure will bend towards the negative electrode/cathode, as depicted in Figure 1b. The volume change happens due to movement of the charge balancing anions in and out of the polymer layers, and perhaps some solvent molecules move inside the polymer layers, due to osmotic effects, to balance the ionic concentration. The charge transfer between the anode and cathode determines the volume change. The bending angle and blocking force output of these actuators are proportional to the input voltage, which is as low as 1V. It is the out of scope of this paper to provide a detailed performance characterization of the actuators. It is recommended to refer to our previous work [5, 6, 8].

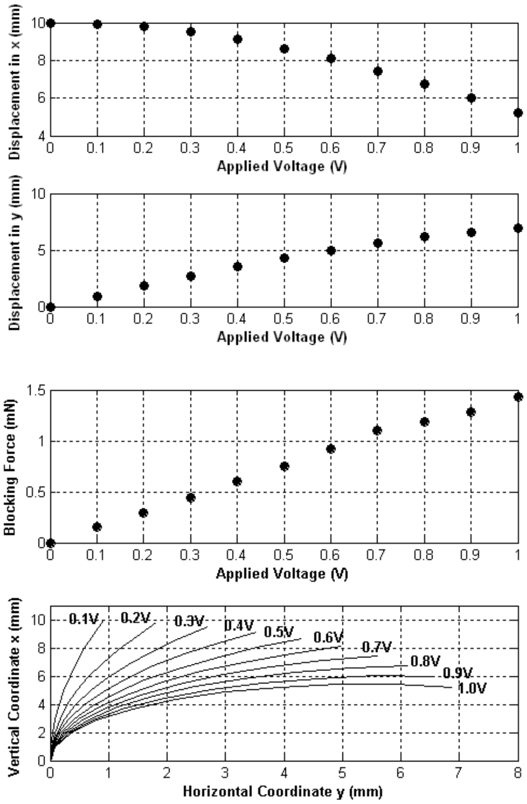


Figure 3: The experimentally determined blocking force, the x-y coordinates of the actuator tip under a range of voltage inputs. The bottom plot is the predicted actuator bending shapes using the experimental tip coordinates x-y.

III. DESIGN SELECTION AND ANALYSIS

The critical elements of the propulsion system are the polymer actuators. The actuator imposes design limitations based on its force output depending on its geometric dimensions, especially length; the shorter the length, the higher force output. Further, force output to the actuator weight ratio is quite high which suggests that these actuators are very suitable to miniaturization. The bending displacement is another important consideration to determine the stroke of the crawling device.

The bending displacement and blocking force outputs of the actuators used in constructing the propulsion were experimentally measured using the measurement setup described in [6]. The configuration of the actuator with the dimensions of 10 mm x 2 mm x 160 μm under 0.5 V is illustrated in Figure 2. The variation of the experimental bending displacements (top two plots) and the blocking force (third plot from the top) are presented in Figure 3. Both are linearly proportional with the input voltage. Using the geometric relationship between the radius of curvature and the x-y coordinates of the actuator tip (Eq.1), the bending trajectory of the actuator under [0V, 1V] is estimated, and is shown in the bottom plot of Figure 3. It must be noted that the bending form of the actuators is similar to that of the biological ciliates, as detailed in subsection 3.2.

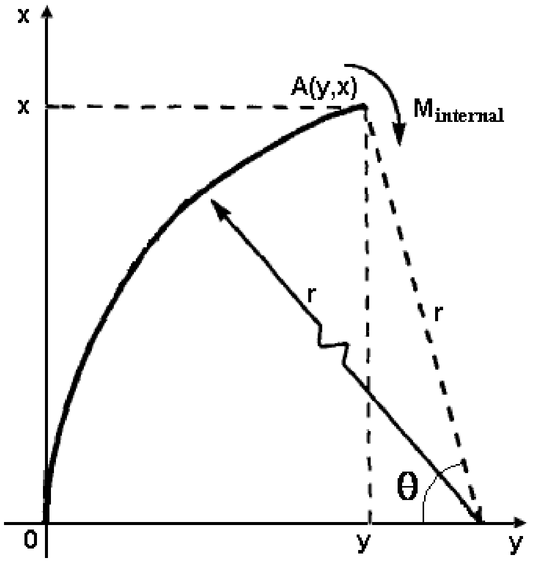


Figure 4: Parameters describing the relationship between the coordinates A(x, y) of the tip deflection and the bending moment.

With reference to Figure 4, the following geometric relationships exist between the radius of curvature and the x-y coordinates of the actuator tip;

$$\mathbf{\frac{1}{r}=\frac{2y}{x^2+y^2},} \qquad (1)$$
$$\mathbf{x=r\sin\theta,\ \ y=r(1-\cos\theta)}$$

Using Bernouilli-Euler beam theorem which suggests that the bending moment on a loaded beam is proportional to the change in the curvature along the actuator length [9], the radius of curvature of a cantilever beam, i.e., the polymer actuator, is given by

$$\mathbf{\frac{1}{r}=\frac{M_{internal}}{EI}} \qquad (2)$$

where $M_{internal}$ is the bending moment induced upon the actuator as a result of an electrochemomechanical process. E and I are the effective modulus of elasticity and the area moment of inertia of the actuator, respectively.

It must be noted [10-14] that many bio-inspired legged locomotion systems involve jointed limbs, while the polymer actuators are limited to a single degree of freedom planar movement. This constraint precludes the effort to achieve any form of bio-mimicry, but instead limits any form of legged locomotion to the bio-inspired type. In fact, this can be seen as beneficial in the fact that dramatically simplifies any legged locomotion and grants the freedom to consider all types of locomotors, not only those which allow mimicry.

Actuator blocking force acts unidirectional to an applied potential, and the polarity must be reversed to achieve force output in the opposing direction. As a design constraint, this property of the actuator can be summarized by the assertion that the simplest method of actuator operation is unidirectional, but in unidirectional operation force is only output in one direction, as shown in Figure 1b. Therefore, the chosen design should begin locomotion at the state of lowest potential (both physical and electrical) using the actuators to raise the potential to achieve locomotion and allow the payload to aid in returning the actuators to their ground state.

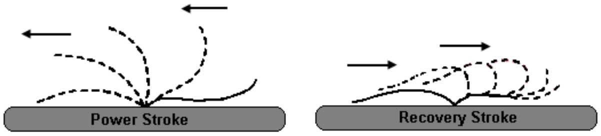


Figure 5: Cilia beat cycle consisting of the recovery and power strokes [15].

A. Selection Criteria

A number of selection criteria is accepted to evaluate various locomotion systems ranging from a limbless (worm-like) locomotion to a cilia locomotion. The criteria are simplicity, the overall weight and size, number of actuators, adjustment, simple control algorithm, and autonomy.

Overall, the actuators provide a compact design and simple operation, thus, simplicity in form and function yields a design that will accentuate this attribute of the polymers. Simplicity in overall design and implementation naturally reduces size and weight, which aides in autonomy. Additionally, reducing the number of actuators required for locomotion reduces size, weight, complexity, and also power consumption, which aids in autonomy. Adjustment is a very broad criteria referring to creating an adjustable design by allowing some methods of parameter variation in a quick, easy, and non-destructive manner. However, this criteria works directly against creating a simple and efficient design so care must be taken to work in adjustments in a straight forward manner. Autonomy relates to all the criteria, but mainly to the fact that any circuitry will need to be carried so reduction in weight or power consumption works directly toward this goal. In the light of the design limitations associated with the polymer actuator and the design criteria, a cilia based locomotion system was chosen.

B. *Cilia Locomotion*

Cilia are typically found in two different environments. First, they present in an aqueous environment performing locomotion as the result of coordinated beating of short cilia (15um) [16]. Second, cilia are present in organs and these tiny hair-like appendages operate as a conveyor system to transport mucus out of the organ. In order to analyze how cilia locomotion may be applicable to this research project, it is best to look at the beat cycle of cilia, as shown in Figure 5. The overall stroke can be broken into a power stroke and a recovery stroke. During the power stroke the cilia is stiff and extended, and moves opposite the direction of motion, while it becomes flexible and bent in the recovery stroke in order to bring the cilia forward for another power stroke [16]. Conversely, if the cilia are fixed in place, the stroke will result in a conveyor action to transport mucus, or debris. The combined stroking of cilia results in forward locomotion of the organism or the forward conveyance of matter.

Looking closer at the architecture of cilia demonstrates the remarkable similarities between the structure and action of cilia and that of conducting polymers. Cilia locomotion on a small scale results in a naturally simple and fundamental method of locomotion. Within this study, it is most effective to view individual cilia as appendages for locomotion so that combining the fundamentally basic stroke of motion along with the principle of stability from limbed locomotion can provide a fundamentally simple and effective form of locomotion. Before building a prototype, we established its virtual design animation to identify potential practical issues such actuator placement and easy assembly, and timing diagram of the actuator powering system. The snap shots of the cilia-inspired propulsion system are shown in Figure 6.

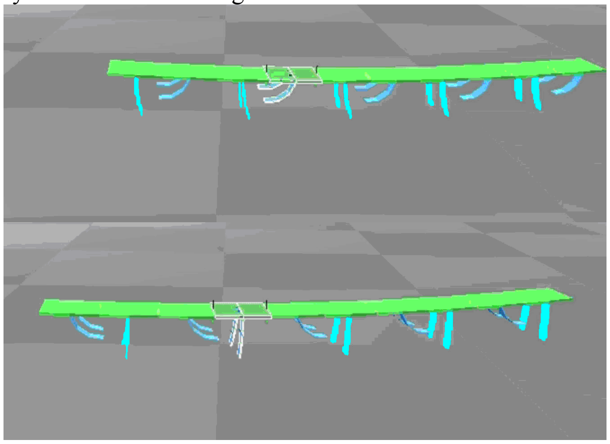


Figure 6: The snap shots of the virtual mini-crawling system. This virtual model has 10 x 2 legs.

IV. TESTING DESIGN CONCEPT EXPERIMENTALLY

After realizing the quasi-static force and kinematic analyses of the polymer actuators, the actuation cycle is determined [17]. Actuation of the polymers uses two separate inputs capable of generating three distinct circuit states resulting in three different bending actions from the actuator. Circuit states can be described as: (i) charging, a potential difference is applied across the polymers resulting in polymer flexing; (ii) discharging, a zero potential is applied to the polymers by shorting directly across them resulting in polymer relaxation or straightening; and (iii) open circuit, no circuit exists across the polymer so it will remain in the identical state to the previously applied potential, provided that there are negligibly small charge leakage and creep. With reference to the actuation state of the actuators over one cycle, the synchronization of the two inputs for a 4-legged locomotion system is developed and is shown in Figure 7.

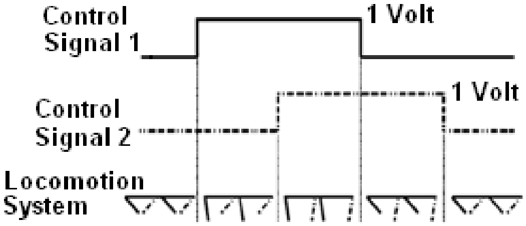


Figure 7: Actuation diagram of the actuators as the legs of the locomotion system.

A. *Experimental Setup*

The experimental setup, consisting of three major components: the body, the joints, and actuators, was built, as shown in Figure 8. A test circuit was also developed to supply the appropriate control signals to the polymer actuators. A complete conveyor system is put into operation to assess the locomotion capability of the cilia-inspired system.

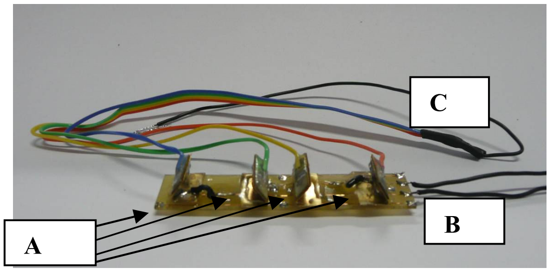


Figure 8: The body part (printed circuit board) of the experimental system to verify the locomotion system as a conveyor system. A, B and C are the magnetic contacts, signal wires and ground wires, respectively.

The body of the setup performs the two main functions of holding the joints in place and delivering electrical power to the joints, and ultimately the legs of the robot. A compact Printed Circuit Board (PCB) was built, suiting the experimental purpose since it is exceptionally light weight and allows electrical power to be delivered to any location on the board, which negates the use of cumbersome wires and electrical connections. The solution to designing a method of effectively clamping the polymer between electrodes in a compact manner is to use magnet clamping. In the design, the leg bracket itself acts as one electrode while the opposite electrode is attached via a wire allowing it to move freely. Magnetic force will fasten the polymer in between the two, as shown in Figure 9. This is accomplished using a non-ferrous and solderable material for the bracket and a ferromagnetic material for the opposite electrode. A magnet was bonded to the back of the bracket providing the required magnetic force. Each electrode was gold coated to prevent corrosion. Additionally, the bracket allows limited variation in polymer mounting angle as desired in initial design.

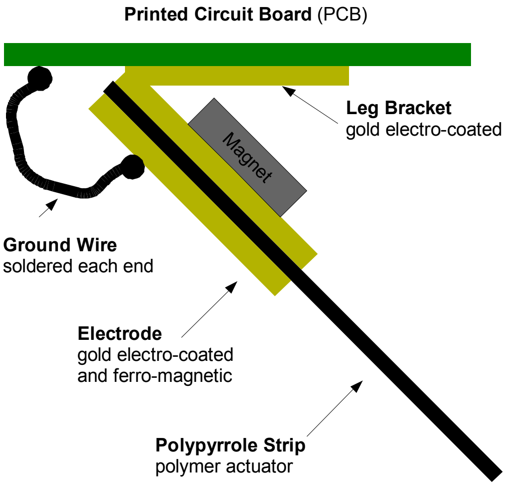
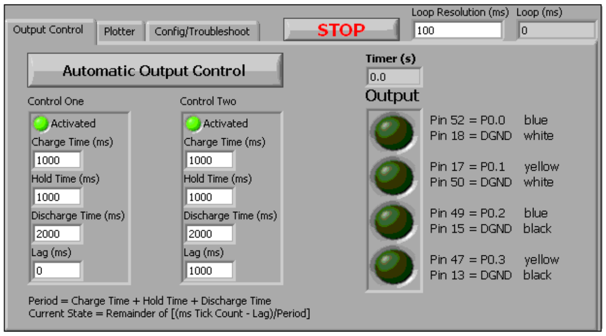


Figure 9: Illustration of the polymer actuator connection to the printed circuit board.

Perhaps the most significant component of this design is based on the legs used for locomotion. As the active actuating part of the robot, any movement to establish locomotion must be generated by these legs. In order to provide the greatest chance for success, the initial design is selected to achieve the greatest force output while providing the widest possible base for stability. Force output and bending displacement in polypyrrole actuators exhibit a trade-off relationship [18-21]. Force output is achieved by increasing the width or decreasing length of the actuator, but increase in width causes actuator curling, and decrease in length of the actuator limits the possible locomotion achieved per cycle. Polymer width of 4 mm is selected to limit the curling effect and obtain a smooth and predictable output. Additionally, actuators are made at a length of 15 mm allowing 5 mm for clamping and 10 mm of the free length for actuation. The overall thickness of the actuators used in the prototype testing was 160 μm.

B. *Control Software*

Software allows manual control or automatic control of the state of each digital output. Control of the TTL (transistor-transistor-logic) signals for switching the necessary relays is accomplished using National Instruments hardware, PCI-6229, and software, LabVIEW. The software has been used to create a program controlling the output of four separate digital lines on the PCI-6229 card for individual control of each of four relays.



Loop Resolution (ms) 100
Loop (ms) 0
Timer (s) 0.0

Control One
Activated
Charge Time (ms) 1000
Hold Time (ms) 1000
Discharge Time (ms) 2000
Lag (ms) 0

Control Two
Activated
Charge Time (ms) 1000
Hold Time (ms) 1000
Discharge Time (ms) 2000
Lag (ms) 1000

Pin 52 = P0.0 blue
Pin 18 = DGND white
Pin 17 = P0.1 yellow
Pin 50 = DGND white
Pin 49 = P0.2 blue
Pin 15 = DGND black
Pin 47 = P0.3 yellow
Pin 13 = DGND black

Period = Charge Time + Hold Time + Discharge Time
Current State = Remainder of [(ms Tick Count - Lag)/Period]

Figure 10: Front panel of the LabView software for controlling polymer actuators.

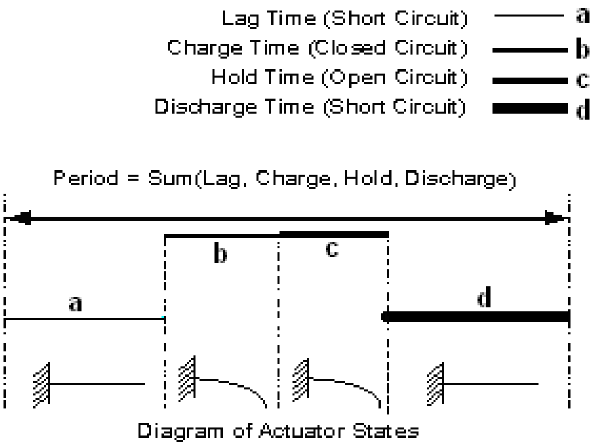
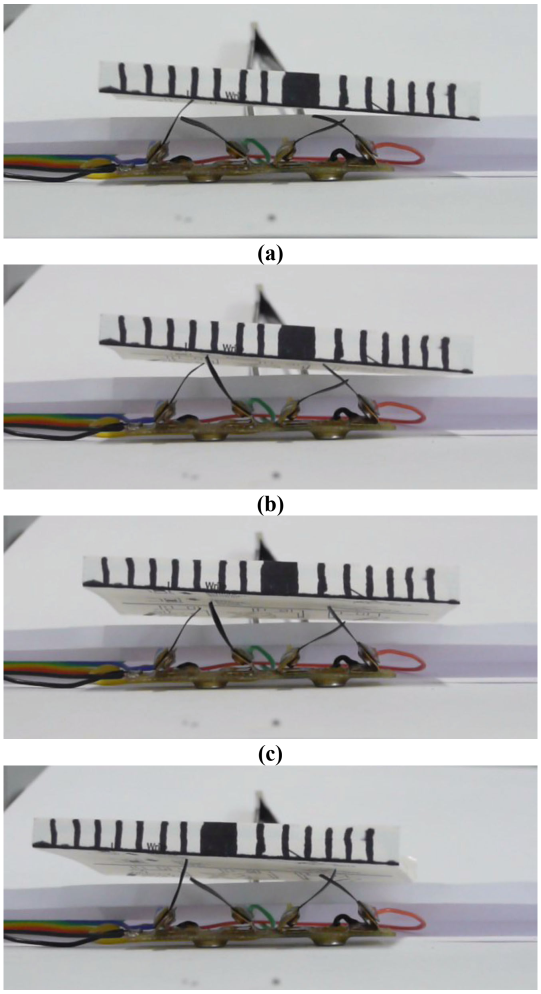


Figure 11: Actuator states as a resulting of the inputs applied according to the timing parameters.

The front panel, or user interface, shows the variable parameters of the program that allow complete control over the state of each of the four relays, as shown in Figure 10. Manual control is enabled whenever 'Automatic Output Control' is not enabled. Upon enabling output control, the program uses the parameters in the 'Control One' and 'Control Two' blocks to output the desired signals to the relays. Available tuning parameters consist of the length of time the circuit remains in each of the three previously defined states as well as the initial time the circuit remains in the short circuited state before proceeding to the charging state, as illustrated in Figure 11. This initial waiting time is referred to as lag in the software since it was created to address the delay, or lag, before the second pair of actuators should enter the charging state.



(a)

(b)

(c)

(d)

Figure 12: Testing the propulsion system as a conveyor at different instances during the test. Please note that the black rectangle is being conveyed towards left, from (a) to (d).

C. *Testing*

As the weight of the PCB and the magnets was higher than the load carrying capacity of the 4 x 2 polymer actuators used to propel the locomotion system, the setup was inverted to bring it into a conveyor configuration to eliminate the total weight of the PCB and magnets. A strip of paper folded to lend rigidity supplied a convenient transport item. The folded paper was marked to allow ease of analyzing the achieved conveyance. The conveying of the paper was recorded with a camera for analysis and improvement of the proposed design. A number of practical issues associated with the actuators and the contacts, the equal lengths of the actuators, bending angle of the actuators were identified.

The desired control signal was also determined to be most efficient at slightly greater than 90 degrees out of phase and utilizing an increased discharge time. Actuation at greater than 90 degrees of phase difference provides first set of polymers an increased time to lift the transport item, while the second set was able to rapidly reach the item. Increased discharge time is necessary because the actuators take longer to relax than to charge. The actuators have been shown to electrically discharge at the same rate as in charging, but required significant time to return to the original physical location. In fact, the more the polymers are activated the more they maintain a natural curl in the direction of actuation. The conveyor test was successful to demonstrate the propulsion concept. Figure 12 shows 5 snap shots of the inverted propulsion system as a conveyor to move a folded piece of paper to the left. The actuators were applied 1V potential difference, according to the actuation diagram in Figure 7.

V. CONCLUSIONS AND FUTURE WORK

We presented the results and implications of our study into the establishment of a propulsion system, which is inspired from the movement of the cilia and is activated with bending type conducting polymer actuators. After presenting design considerations and selection criteria, a prototype was built and tested as an inverted crawling device, operated like a conveyor system to verify the propulsion concept activated with very low power - dry type conducting polymer actuators. Details of the prototype system are presented and the practical problems encountered during the operation of the conveyor are discussed. The successful testing suggests that conducting polymer actuators can be employed to make functional devices.

Future work involves improving the force output of the actuators, assembling the polymer actuators with their neutral position is almost parallel to the ground, and they do not generate a movement which passes the peak point. When the actuators bent over the peak point, it generated a rocking motion; rather than conveying the paper object; it pushed and then pulled back without a net forward translation. It is also our future work to put the power source (battery) and wireless communication modules on board towards an autonomous and wireless pipe inspection system. With the fabrication of micro-sized polymer actuators [22], we also aim to build a fully autonomous and wireless micro robotic system based on conducting polymer microactuators.

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