Representation of a Conceptual Design for a Rectilinear Motion Polymer Actuator

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Abstract: A number of different alternative actuation methods have been under active development for some specific applications where the traditional electromechanical actuators are difficult to apply. Recently, many of these substitutes are trying to employ new smart materials like electroactive polymers. However most of the polymeric materials are flexible and vulnerable so that they normally can not sustain external forces. Although the materials have shown a good potential to be used for alternative actuation mechanisms, no tangible industrial application is yet presented because of the reason. A conceptual design for a rectilinear motion actuator using dielectric elastomer is presented in this article. The introduced design concept might enable to produce fairly controllable rectilinear motions for various applications and the presented prototype actuator system is fully packaged in a small unit and controlled by a standard communication interface.

Keywords: Antagonistical drive, dielectric polymer, electroactive polymer, rectilinear motion actuator.

1. INTRODUCTION

In various industrial application fields, polymers are recently getting more attentions as a new type of energy transformers mainly thanks to their lighter weight and higher efficiency compared to the traditional electromagnetic transducers. Although several polymeric energy transforming materials are available for current transducer researches, electroactive polymers (EAPs) seem to have a dominant potential to be a successful alternative actuator [1-3]. Various EAPs including ionic polymer metal composites (IPMC), conducting polymers (CP), polymer gels, dielectlic elastomers, and piezoelectric polymers are used for various transducer constructions. However most of the constructions have technical limitations so it is yet far from actual implementation of industrial applications. In spite of the technical difficulties their application areas have been rapidly expanding by many frontier researchers especially who are in robotics and bio applications.

In general, EAPs are to be categorized in two groups, ionic and non-ionic by their energy transduction characteristics. Recently, non-ionic polymers such as dielectric elastomer are more preferred and have more potential to be applied to industrial applications where large actuation forces are necessary [4,5]. There are a few dielectric elastomers like polyurethane and silicone currently available for either laboratory or industry level applications. The basic operation of the material as an actuator is simply that the polymer intrinsically deforms either in expanding or in contracting when electrical voltage is applied to electrodes coated on its surfaces. Basic principle actuation mechanisms are well documented in many publications [6,7]. Although numerous authors recently have presented many different polymer actuation concepts, little is demonstrated for industrial applicability of the idea and controllable actuator system that can be implemented with reasonable amount of control actions.

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In the present work, an antagonistically configured dielectric elastomer actuator is proposed. Given the material and the geometrical constraints which should be well accounted for controllable actuation, it successfully delivers controlled bidirectional rectilinear mechanical motions by changing its compliance and exerting force. Guaranteed controllability of the motion with simple control law is of course one of the most important design requirements of any kind of actuators. Especially when they are applied to human-muscle-like motion generators, simple architecture and easy control should be ensured. The proposed actuator design not only satisfies both requirements but can be manufactured with ease. In the previous work, the actuators are made in ad hoc fashion with single polymer film layer due to lack of efficient fabrication method [8,9], although they showed a feasibility of antagonistic driven actuator architecture. One of the significant drawbacks of the design is fragility of the film by normal direction external forces to its surface. Recognizing the disadvantages of the previous designs, the present work employs a new actuator concept using dual films so that it successfully bears heavy transverse loads. This design enables to deliver rugged rectilinear actuation mechanism as well as expandability to a multi-degree-of-freedom actuation.

The succeeding sections of the paper are organized as follows. First, basic operation principle of the polymer actuator is reviewed. Next a generic design of the new antagonistically configured actuation concept is presented. A constitutive model of the principle actuation mode is considered. Third, a rectilinear motion actuator called Rectilinear Polymer Motor is fabricated and tested. Finally, a feasible multi-DOF actuator design concept which could be simply augmented from the presented rectilinear mechanism is suggested.

2. BASIC OPERATION MECHANISM

The actuator developed here is fabricated with dielectric elastomer. Principle actuation physics of the material is elaborated and well documented in some publications [7,11-13]. The principle operation is similar to the electromechanical transduction of a parallel two plate capacitor. When a voltage potential is applied across the polymer film coated with compliant electrodes on both sides, the material is compressed in thickness and expands in lateral direction. By virtue of this contraction caused by the charged electrical energy across the thickness of the material, mechanical actuation force is generated. This physics couples mechanical and electrical energy domains so that energy transduction happens. The effective mechanical pressure along the thickness direction by electrical input is given by

$$\sigma_e = -\varepsilon_o \varepsilon_r E^2, \quad (1)$$

where E is an applied electric field, ε_o and ε_r are the electric permittivity of free space and the relative permittivity respectively. Mechanical actuation could be acquired through either the effective pressure caused axial contraction or the lateral expansion of the dielectric elastomer block.

Although the way to acquire the mechanical actuation is straightforward as explained with the basic operation, there is still a significant limitation of the operation that is to be used for an actuator due to its low exerting forces. It is simply because the actuation is provided by the soft thin polymer film configuration. In addition, the thin polymer film used for the basic operation can be easily ruptured by small normal forces or buckled by lateral forces. Moreover the operation is hardly controlled so that it is practically just a simple movement rather than actuation.

3. ANTAGONISTICALLY CONFIGURED ACTUATION

3.1. Prototype design

Noting the fundamental limitations of the basic actuation mechanism, a noble design of antagonistically configured actuation mechanism is introduced. Detailed architecture of the mechanism is depicted in Fig. 1. In the configuration, two sheets of dielectric polymers are fixed to each ends of a rectangular rigid

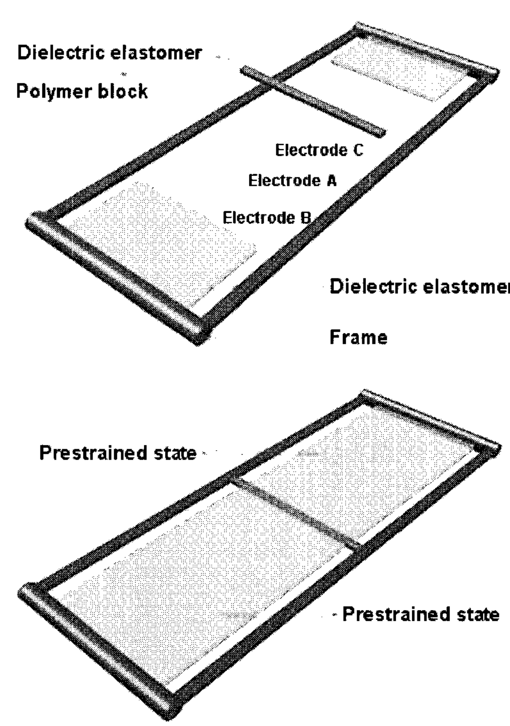

Fig. 1. Construction of antagonistically driven actuator mechanism.

frame. Then the fixed polymer sheets are stretched to join each other with a rigid bar so that the sheets are prestrained/preloaded. With the prestrain effect of the configuration, a polymer sheet may produce relatively larger displacement [13], although a recent study proves that it is not necessary for acquiring a large strain [10]. Having the prestrained polymer sheets connected together, a combination of push-pull forces produces larger actuation displacements. For example shown in Fig. 2, application of electric field to a dielectric polymer sheet at right hand side of the actuator expanses the sheet and it breaks mechanical force balance of the two connected sheets. Then the center bar moves to left until a new force equilibrium is established. Removing the applied electric input retracts the extension so that the center bar moves to right back to the original position. The actuation can easily be reversed by applying the input to the left polymer block.

An antagonistic polymer actuator has been built based on the idea. A prototypes has been made for the experiments. It is built with Nusil CF19-2186 thickness of 65μm, size of 19.5mm^3 and coated with silver paste for the electrodes. The prototype for the testing is shown in Fig. 3. As applying voltage across A-C electrodes, displacement of the output terminal is measured with a laser displacementmeter (Keyence).

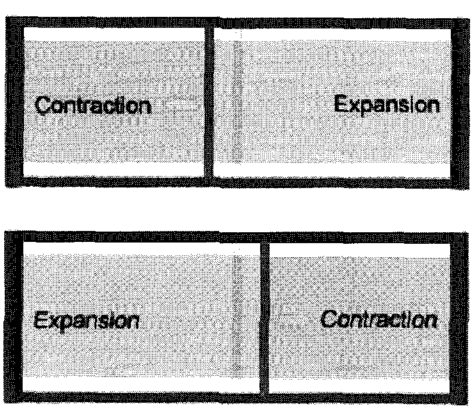

Fig. 2. Antagonistic operation.

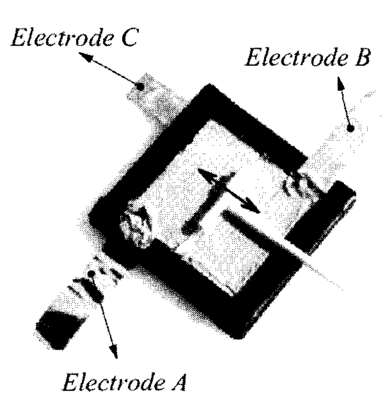

Fig. 3. Prototype actuator.

3.2. Constitutive interpretation of the basic actuation mode

The physics of the proposed actuation can be explained with a two-plate capacitor [14]. It operates in both electrical and mechanical energy domains. The model therefore has to couple two different energy domains with stored potential energy. Constitutive relation of a typical two plate capacitor is

$$q = \Phi_c(e), \tag{2}$$

where q is generalized displacement and e is generalized force. It is of course that time derivative of the energy variable q yields power conjugate of the generalized force. For a linear capacitor the constitutive equation (2) is to be replaced by

$$q = Ce, \tag{3}$$

where C is the capacitance. Then the energy W stored in a capacitor is given by

$$W = \int P\, dt = \int \frac{q}{C} dq = \frac{q^2}{2C}, \tag{4}$$

where P is power. For the dielectric elastomers, the capacitance is given by

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}, \tag{5}$$

where ε_0 and ε_r are the free space permittivity and relative permittivity respectively as aforementioned. And A is effective electrode area whereas d is the separation between electrodes. Since most of elastomers are incompressible, volume of an elastomer block can be assumed as a constant without loss of generality and Poisson's ratio ν is 0.5 [12]. This assumption permits

$$A_x \cdot x = A_y \cdot y = A_z \cdot z = V_0, \tag{6}$$

where V_0 represents the initial volume of the elastomer and x, y, and z are width, depth, and height/thickness of the volume. A_x, A_y, and A_z are the corresponding cross-sectional areas. Therefore the stored energy of the elastomer is

$$W = \frac{q^2 z^2}{2\varepsilon_0 \varepsilon_r V_0} = W(q, z). \tag{7}$$

Note V_0 is a constant and q and z are generalized displacements that are true coordinates. Hence the generalized force associated with q is

$$\frac{\partial W}{\partial q} = \frac{q z^2}{\varepsilon_0 \varepsilon_r V_0}, \tag{8}$$

which should be the electrical input voltage V.

Likewise, the generalized force corresponding to z is to be

$$\frac{\partial \mathcal{U}}{\partial z} = \frac{q^2 z}{\varepsilon_0 \varepsilon_r \mathcal{A}_0}, \tag{9}$$

that is the mechanical force applied along the thickness direction which is designated as z direction in the present formulation. For the construction of energy storing capacitor, the stored energy should be conserved so that Maxwell's reciprocity relations must be satisfied [15]. And the relations should be

$$\frac{\partial}{\partial z}\left(\frac{\partial \mathcal{U}}{\partial q}\right) = \frac{\partial}{\partial q}\left(\frac{\partial \mathcal{U}}{\partial z}\right) = \frac{2qz}{\varepsilon_0 \varepsilon_r \mathcal{A}_0}. \tag{10}$$

Therefore, the constitutive relations equations (8) and (9) are valid and could be replaced by

$$V = \frac{z^2}{\varepsilon_0 \varepsilon_r \mathcal{A}_0} q, \tag{11}$$

$$F_z = \frac{q^2}{\varepsilon_0 \varepsilon_r \mathcal{A}_0} z, \tag{12}$$

where V is voltage difference across two electrodes and F_z is mechanical force along thickness direction.

3.3. Antagonistically driven rectilinear actuator

As indicated in the previous sections, there are critical flaws in the basic operation mechanism that are the small exerting forces and the lack of controllability. Although the limitations are partially alleviated by introducing the antagonistic driving configuration as shown in the previous sections, it is still difficult to be used for an industrial application. A new design concept named *ANTagonistically-driven Rectilinear Actuator* (ANTRA) is hence proposed. Its assembly concept is illustrated in Fig. 4. The actuator is constructed with two films made with dielectric elastomer. Each film is mounted on a circular frame that works as a ground electrode, which is marked as electrode C in the figure. The two mounted films are to be prestrained/preloaded by sandwiching a pretensioning rod. Once the assembly is done, the rod is positioned and remains at the elastic force equilibrium of the two prestrained elastomer units. If the elastic force balance is broken by any reasons such as electrical input to one of the elastomers, the rod will move either upward or downward and stop at a new equilibrium position. This is the fundamental operating principle of the proposed actuator.

More detailed illustration about the proposed working mechanism is provided in Fig. 5. When

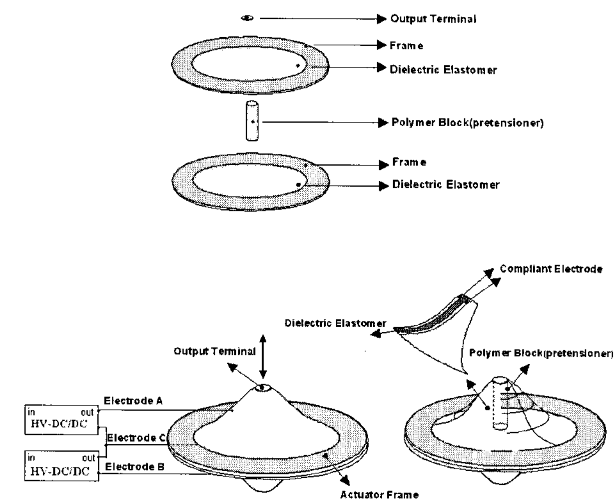

Fig. 4. Schematic view of proposed actuator design concept.

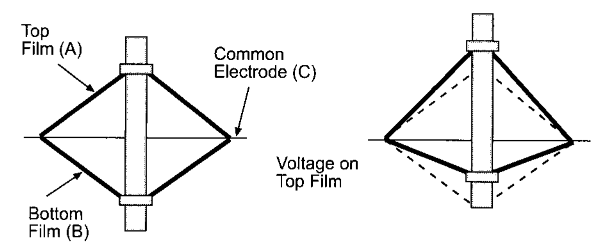

Fig. 5. Principle actuation mode.

electric input is applied to electrodes A and C across the top film, the dielectric elastomer film expands and it results in breaking the initial strain force balance. Hence the rod will move upward and stop at a new equilibrium position. Since both polymer films are constrained each other through the rod, the proposed actuator motion should be fairly controllable. In fact since the antagonistically prestrained elastic forces dominate other system mechanical parameters such as mass and damping, the movement of the actuator should be stable and controllable.

The actuator is to return back to its original state as soon as the input is removed. The actuation can be of course easily reversed by applying electrical input to the bottom film. By the same token, a push-pull actuation is possible by alternating actuation of the two. Some example patterns of the actuator driving are listed in Table 1. This paradigm provides four distinct working modes such as forward, backward,

Table 1. Rectilinear actuator driving paradigm.

State	Electrode (ABC)
Stiff state	$\ominus\ominus\ominus$ or $\oplus\oplus\oplus$
More compliant	$\oplus\oplus\ominus$ or $\ominus\ominus\oplus$
Action toward A	$\oplus\ominus\ominus$ or $\ominus\oplus\oplus$
Action toward B	$\ominus\oplus\ominus$ or $\oplus\ominus\oplus$

more-compliant, and more-stiff. This feature can be applied for biomimetic mechanisms.

4. RECTILINEAR POLYMER ACTUATOR DESIGN

Having feasibility about control of the proposed actuation concept, a single-DOF rectilinear actuator unit is constructed. A schematic cross-sectional view of a fully packaged actuator assembly is shown in Fig. 6. As depicted in the figure, all of the essential components including dielectric elastomer actuator, driving circuits, micro controller, and RS-232C serial interface are integrated in a unit. A fully assembled actuator unit that is connected to a communication port is shown in Fig. 7. Although this actuator unit is made without any specific application in mind, nothing is confined about its application areas. The thrust force and physical size of the actuator are potentially scalable in any dimension so that it could be applied for various actuator operations ranging from micro robotics to consumer electronics. Moreover it generates thrust force by a true rectilinear mechanism without any mechanical transformers that guarantees higher energy efficiency, quiet operation, and easy control. Table 2 describes specifications of the presented sample actuator unit.

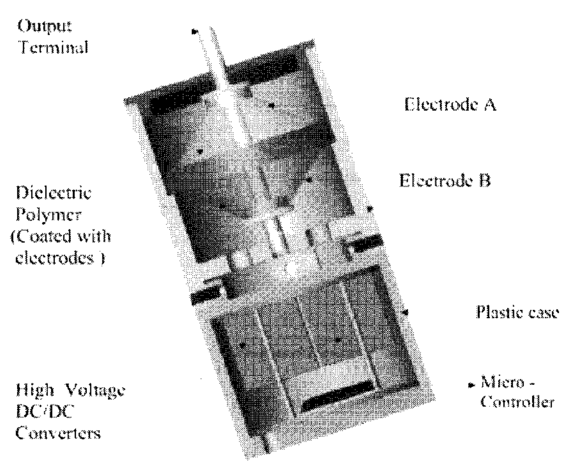

Fig. 6. Cross-sectional view of rectilinear polymer actuator design.

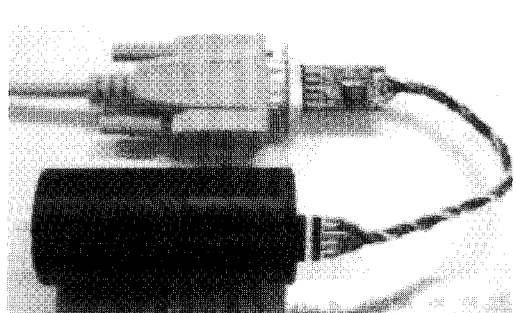

Fig. 7. Packaged prototype connected to RS-232.

Table 2. Specification of prototype.

Item	Specifications
Size	34mm[D] X 65.4mm[L]
Total weight	50g (actuator 1.9g)
Stroke	2.4mm
Thrust force	10gf
Speed	1mm/sec

5. MULTI-DOF ACTUATOR DESIGN

The proposed concept of the single-DOF rectilinear polymer actuator can be easily extended for a multi-DOF motion actuator as illustrated in Fig. 8. The actuator consists of eight polymer film sections, four sections on each side. It could be manufactured by simply partitioning the elastomer surface and applying electrode paste separately on each partitioned area during electrode coating process. Since each polymer section is to be packaged separately, each quadrant can be controlled independently. A proper combination of individual motions of each section might provide continuous multi-DOF actuation. For example, when sections *d* and *h* are actuated, the output terminal (mass) moves to positive *x* direction. Fig. 9 shows a driving method for creating translational motions. If sections *c* and *f* are turned on as a nonsymmetric input pattern, the output terminal will be tilt with respect to positive *x* axis. Then if the control action succeeds to provide electrical input to sections *d* and *e*, the terminal will rotate about positive *y* axis. The further continuous control action with proper adjustment of input voltage during the transition of the rotation axis enables to keep the terminal in smooth rotation. Some typical actuator driving examples are shown in Table 3.

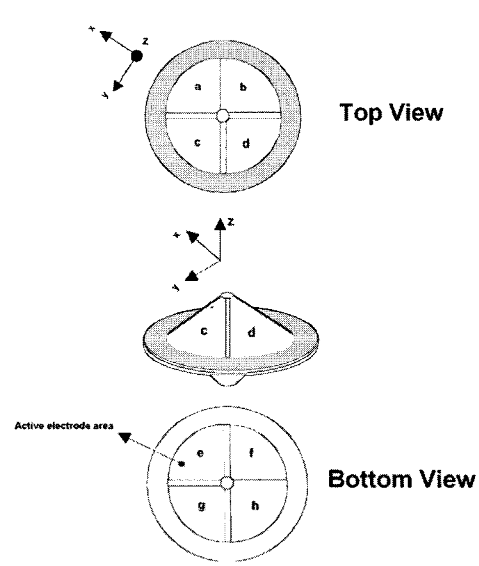

Fig. 8. Design concept of a Multi-DOF polymer actuator.

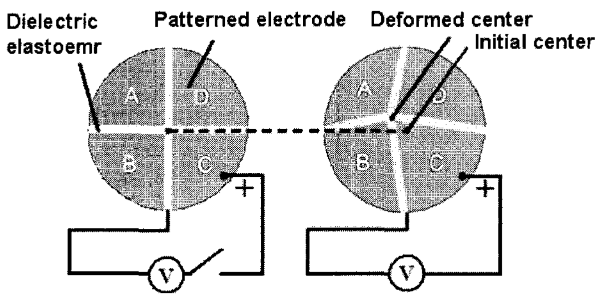

Fig. 9. Translation motion of the actuator.

Table 3. Typical examples of actuator operation.

Movement	a	b	c	d	e	f	g	h
$-x$ axis tans.	–	–	–	+	–	–	–	+
$+x$ axis trans.	+	–	–	–	+	–	–	–
$+x$ axis rot.	–	–	+	–	–	+	–	–
$+z$ axis trans.	+	+	+	+	–	–	–	–
$-z$ axis trans.	–	–	–	–	+	+	+	+

6. CONCLUSION

Although extensive efforts have been dedicated to the polymer actuation research and remarkable results of the area have been delivered, very limited number of publications address actual industrial applications. Difficulty of designing a controllable device that can also sustain significant amount of mechanical loads hampers application of the polymer material to industrial actuator design.

A new rectilinear motion actuator made with dielectric elastomer is presented. Although the concept developed in the present work extends a basic operation of dielectric elastomer introduced in previous publications that remain merely at a level of simple material movement, it successfully delivers a controllable thrust force generation method. The design adopted here is very attractive, since it leads to a pure rectilinear direct actuation that could be more energy efficient, less noisy, easy to control, and could be packaged in a small form factor. Although the presented design is more likely generic at this moment, nothing in the concept precludes the extension to further industrial applications. The introduced rectilinear single-DOF actuation idea is easily extended to a multi-DOF actuator design.

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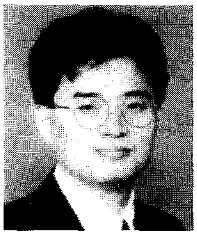

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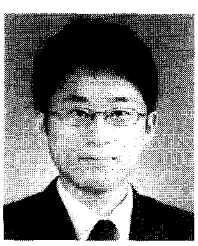

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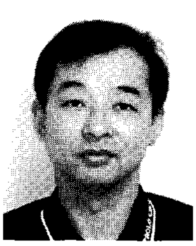

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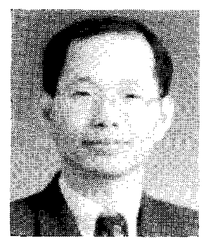

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