On the Design of Large Degree-of-Freedom Digital Mechatronic Devices Based on Bistable Dielectric Elastomer Actuators

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***Abstract*—Binary actuation has been proposed to reduce complexity in robotic and mechatronic systems. However, a relatively large number of binary actuators are required to achieve the accuracy necessary for practical applications. Conventional actuators are not practical for such large degree-of-freedom (DoF) devices. Here, a dielectric elastomer (DE) actuator is developed for these applications. It is shown that DE actuators have high energy densities, light weight, low cost, and large displacements. Hence they could potentially make large DoF binary systems practical. DE actuators proposed here consist of thin electrically sensitive elastomer films that are mounted in a flexible frame that incorporates a passive bistable element. The frame prestrains the film and provides a restoring force that allows the actuator to operate bidirectionally. A simple experimental prototype 6-DoF binary manipulator demonstrates the concept.**

***Index Terms*—Binary actuation, bistable mechanism design, hyperredundant manipulator, polymer actuators.**

I. Introduction

FUTURE robotic applications, ranging from space exploration to medical procedures, will require robotic devices and components that are simple, robust, lightweight, inexpensive, and easy to control. Large degree-of-freedom (DoF) binary-actuated systems have been proposed to meet this need [1]–[4].

Binary actuation can be viewed as the mechanical analog to digital electronics, where each actuator behaves in a discrete manner, maintaining one of two possible states. Design is greatly simplified since low-level feedback control is virtually eliminated, along with the associated sensors, wiring, and electronics. It has been shown that the performance of a binary mechatronic system approaches that of a continuous system as the number of binary actuators in the system increases [5].

An example of a binary-actuated system is the binary robotic articulated intelligent device (BRAID), which has been proposed as a potential building block of practical robotic systems [6]. The BRAID consists of a serial chain of 3-DoF parallel platform modules (see Fig. 1) [7]. In simulation studies, these devices were shown to be kinematically capable of executing practical tasks, such as instrument placement for planetary exploration and legged locomotion through rough terrain (see Fig. 2) [5]. Other explored applications include industrial and medical devices [8]. Simulations suggest that less than 100 DoF will provide sufficient resolution for many practical tasks, and that the associated computing requirements for solving their inverse kinematics are reasonable [5].

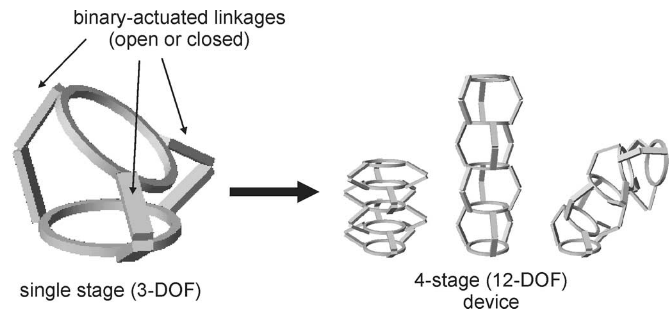

Fig. 1. BRAID kinematic structure.

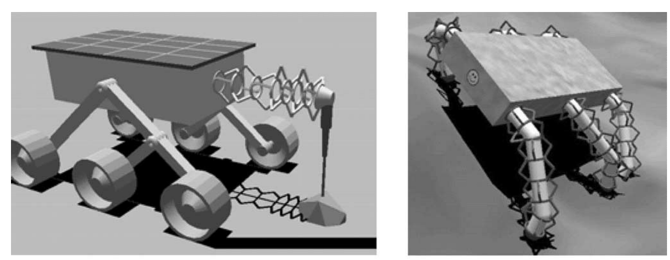

Fig. 2. BRAID applied to planetary exploration. (a) Manipulator on a conventional rover. (b) Legs of a walking robot.

To date, the primary challenge to implementing practical large DoF binary mechatronic systems has been actuator technology. Using electromagnetic, pneumatic, or hydraulic actuators yields extremely heavy and complex systems [9], [10]. In recent years, important progress has been made in the area of dielectric elastomer (DE) actuators [11]–[13]. DE actuators are based on a thin electrode-coated elastomer film that expands in area in response to an electric voltage. Under laboratory conditions, these actuators have achieved very high energy densities, significantly exceeding those of conventional technologies such as electromagnets, although practical implementations have achieved somewhat lower performance [12], [14].

These actuators have the potential to overcome the limitations of conventional actuators and serve as a key enabling technology for large DoF binary robotic and mechatronic devices. They

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are very lightweight and simple compared to conventional actuators. They can achieve strains above 100% and can therefore be implemented in a direct-drive fashion [15]. Motion amplification, which is typically required for novel actuators such as shape-memory alloy or conducting polymer, is not needed for DE actuators. This further reduces complexity, weight, and cost.

Conversely, binary operation mitigates many of the potential shortcomings of DE actuators, making the marriage of DE actuators and binary mechatronics very good. DE actuators are inherently compliant and can be sensitive to creep and current leakage while under power for long periods of time. The switching nature of binary devices mitigates this problem by using the actuators only to toggle the mechanical configuration of the system. Disturbance loads on the device are absorbed by the mechanical structure of the device rather than the actuators, and power need only be applied intermittently to toggle the device configuration.

In this paper, a design approach is presented for DE actuators that achieve performance necessary for binary mechatronic systems. The key concept is the prestretching of the actuator over a variable-geometry frame, which ensures near-ideal loading conditions on the actuator film and provides an elastic restoring force in the direction of motion. By selecting an appropriate frame geometry, the area expansion of the film can be converted into the linear motion required for an application. These actuators are not fundamentally bistable, and therefore passive elastic bistable elements are incorporated into their frames. Precision binary action is achieved as the bistable element forces the actuator against hard mechanical stops and holds it there without application of actuator power. This element also enhances the force–displacement characteristics of the actuator. The result is an effective bistable actuator concept.

The binary actuator modules are implemented in an experimental 6-DoF prototype device. A previously constructed electromagnetically actuated prototype serves as a reference for comparing DE performance to a conventional actuator technology [9].

II. Background and Literature

A. Binary Robotics

The concept of binary and sensorless robotics was first introduced in the 1960s and 1970s [1], [2], [16]. More recently, increased computation power made the analysis, control, and planning for binary robots feasible [3], [4], [17]. The planning and control of binary manipulators is fundamentally different than that for continuous systems. For example, the inverse kinematics problem for a binary device involves a search through a discrete set of configurations. For a binary system with a large number of DoF, exhaustive searches through the workspace are computationally impractical. Combinatorial search algorithms and genetic algorithms have led to a dramatic reduction in computation time for these problems [4], [5]. It has been shown that computational requirements are reasonable for the planning of systems having hundreds of DoF. These studies also demonstrate that such numbers of DoF allow sufficient precision for many practical robotic tasks.

Low-DoF binary manipulators have been constructed. Examples include a large variable geometry truss (VGT) manipulator constructed from pneumatic actuators [18] and a 30-DoF planar snake-like VGT actuated by dc servo motors and lead screw drives [10]. These systems show that while conventional actuators are acceptable for systems with few DoF, they cannot be readily used for practical systems with very large numbers of DoF. The resulting systems would be excessively complex, costly, heavy, and lack reliability, particularly when used in a serial chain configuration. To date, little work has been done to develop simple, lightweight, and robust binary design concepts. Certainly, practical large DoF binary robotic systems using conventional actuators have yet to be demonstrated. In this study, the potential of using DE actuators for such systems is explored.

B. DE Actuators

The development of DE actuators started in the early 1990s [19], [20]. The identification of new and more effective DE materials has made it a very promising actuator technology, with reported laboratory strains of up to 380% [12], [21]. The use of the actuator for such applications as robots, acoustic speakers, and solid-state optical devices has been proposed [12]. DE materials have been used to power a snake-like manipulator, an insect-inspired hexapedal walker, and an inchworm robot [12], [22], [23]. In these implementations, actuator strains do not exceed a few tens of percent, suggesting that the technology is performing far short of its potential. Closer investigation reveals that the present limitations of DE actuators lie not in the elastomer materials, but rather in the details of their integration into functional actuators and devices [24].

This paper explores the implementation challenges associated with DE actuators in robotic and mechatronic devices. The paper demonstrates that many of these challenges can be overcome by using many actuators in a binary fashion, termed *digital mechatronics*.

III. DE Actuator Module

A. DE Operating Principle

The operating principle of DE is rather simple. A thin elastic film is sandwiched between compliant electrodes, as shown in Fig. 3. As a voltage is applied to the electrodes, the electrostatic forces cause the elastomer to compress in thickness and expand in area [25]. Using materials such as acrylics or silicones for the film, high strains and energy densities can be achieved. The compliant electrodes can be made by coating a conductive layer (such as carbon powder or silver grease) on both sides of the film [26]. To design an effective actuator based on this principle, it is necessary to understand the mechanical behavior of the DE.

The DE that separates the electrodes experiences an electrostatic pressure when a voltage is applied across the electrodes. If both the dielectric material and the electrodes are compliant, then the effective pressure (p) is given by

$$p = \varepsilon\varepsilon_0 E^2 = \varepsilon\varepsilon_0 (V/z)^2 \quad (1)$$

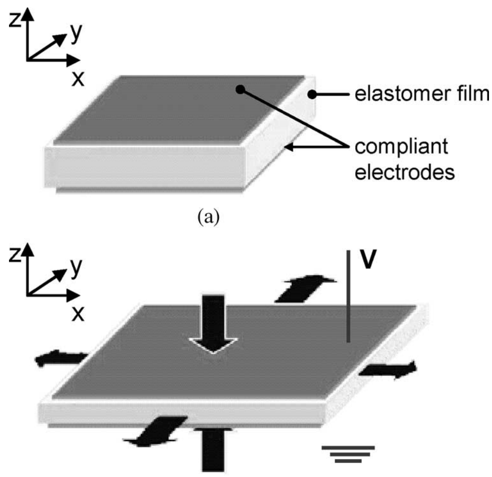


Fig. 3. DE actuator operating principle. (a) Actuator in undeformed state. (b) After application of high voltage (adapted from [20]).

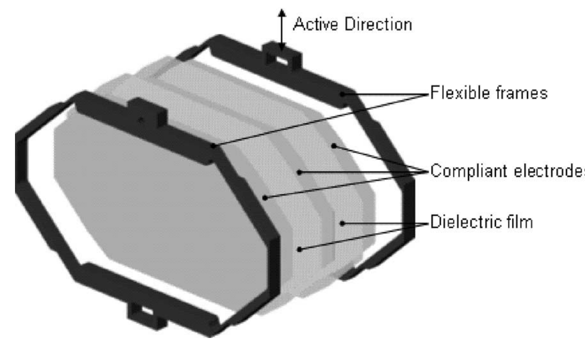


Fig. 4. Embedded flexible frame actuator module. (a) Voltage off. (b) Voltage on.

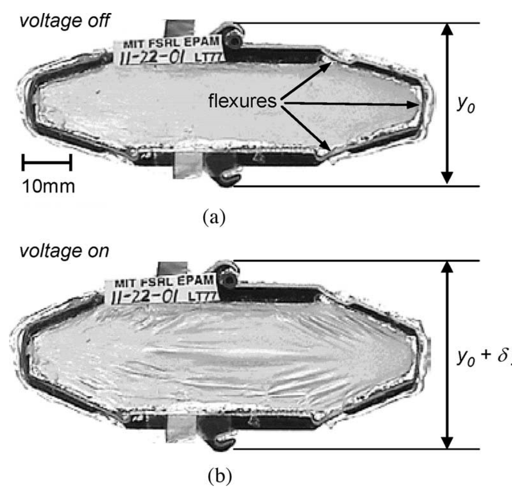


Fig. 5. Actuator module (a) before and (b) after actuation.

where ε is the relative dielectric constant, ε_0 is the permittivity of free space, and E is the applied electric field, which is the ratio of the applied voltage (V) to the film thickness (z) [1], [22]. It is desirable to achieve a large effective pressure, since it determines how much force an actuator can produce. Equation (1) suggests that a high effective pressure will result from a large electric field. The maximum electric field, or breakdown field, for a typical acrylic-based polymer used for DE actuators (VHB 4910) has been shown to increase by more than an order of magnitude when prestretched [27]. Since the electric field term (E) in (1) is squared, prestretching this material can increase the maximum attainable effective pressure by two orders of magnitude. To fully exploit the potential of DE materials, the prestretching of the film is very important in actuator design.

B. Actuator Frames

Many mechanical applications require an actuator that provides linear motion, rather than expansion in area. The challenge is to convert the film's area expansion into linear motion, while maintaining the prestrain boundary conditions on the film.

This research suggests that stretching and then mounting the DE material in a variable geometry hexagonal frame is an effective solution to this problem (see Fig. 4). The frame is kinematically approximated as six links connected by revolute joints. As the frame expands in the vertical direction (the active direction), the enclosed area increases. Prestraining forces are maintained by the elastic hinges at the revolute joints.

In addition to supporting the prestretched film, the flexible frame permits the actuator module to operate under both tension and compression. The film by itself cannot provide compressive forces, as it easily buckles. The frame also strengthens the exposed edges of the film and prevents current arcs from developing around the edges of the film, which dramatically improves lifetime of the actuator.

C. Actuator Module Implementation

Fig. 5 shows a representative embodiment of this actuator design, fabricated by the authors using simple techniques similar to those used by other researchers [27]. This actuator has been implemented by the authors by sandwiching a prestretched VHB 4910 acrylic film between two flexible frames, as shown in Fig. 4. The frames are machined from monolithic pieces of acetal resin (Delrin). Flexures are used for the joints, and are fabricated by reducing the wall thickness of the frame in these areas [see Fig. 5(a)]. To increase the actuation forces, two layers of the dielectric film and electrode sandwich are placed between the frames [13]. A single layer of prestrained dielectric film has a thickness of about 0.1 mm, similar to the thickness of a sheet of paper. Depending on the force requirements, a number of dielectric film and electrode layers could be placed between the frames, in which case the frame would need to be stiffened accordingly to provide the appropriate elastic restoring force.

Fig. 5(a) shows the representative actuator with no voltage applied. The frame is under vertical compression and the elastomer film is under tension. Applying a voltage across the electrodes reduces some of the tension in the film, allowing the frame to relax and expand in height. Fig. 5(b) shows the actuator after a voltage of 5.5 kV has been applied and the frame has relaxed by

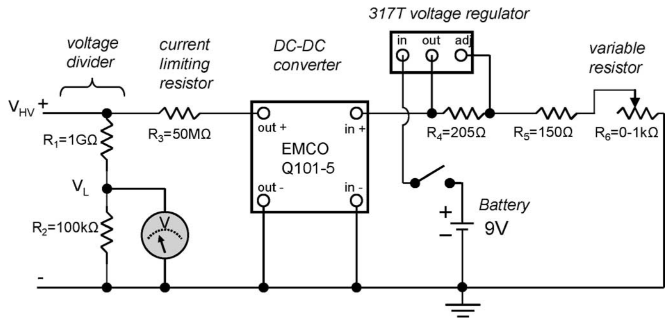


Fig. 6. Circuit diagram for voltage amplifier.

$\delta y = 4$ mm. Removal of the charge causes the actuator to return to its original shape.

In Fig. 5(b) it can be seen that the actuated film starts to wrinkle, indicating that the elastomer is no longer under tension in some areas. The onset of wrinkling was used to determine the maximum practical actuation voltage. Higher voltages yield only marginal displacement gains, at the risk of damaging the actuator.

The actuation voltage for DE materials is very high (in kilovolts), although the actuation currents are very small (in microamperes). The high-voltage requirement does not pose a significant technical challenge since miniature $(1\ \mathrm{cm}^3)$ high-voltage dc–dc converters are commercially available [28]. The circuitry used here is shown in Fig. 6. The system uses a commercial dc–dc converter (EMCO Q101-5) that has a fixed gain of 2000. Its rated maximum output voltage is 10 000 V and its maximum current is 50 μA. All switching and voltage regulation is done on the low-voltage side of the circuit. The power to the dc–dc converter is provided with a standard 9-V battery through a variable voltage regulator. The low-voltage input voltage can be externally adjusted through a variable resistor (R_6). The circuit was designed so that the high-voltage output can be controlled over a range from 5 to 10 kV. On the high-voltage side of the circuit, a current-limiting resistor (R_3) protects the circuitry in the event of a short circuit across the output terminals. Since the high output voltage (V_{HV}) of the power supply cannot be measured with a standard multimeter, the measurement is taken through a voltage divider, which scales the high voltage by a factor of 10^4. The voltage divider resistors also function to drain charge from the actuator after the supply has been switched off.

D. Actuator Performance and Mechanical Model

To evaluate performance, the force–displacement characteristics of the actuator were measured (see Fig. 7). Curves are shown for an actuator at 0 kV, 5.5 kV, and completing a work cycle. The work cycle is generated by first constraining the displacement of the actuator. A voltage of 5.5 kV is applied and the force applied to the constraint is recorded. While keeping the voltage fixed, the constraint is moved until the actuator output force is zero. The voltage is then removed and the process is repeated. The area enclosed by a counterclockwise work cycle corresponds to the work output per cycle [14].

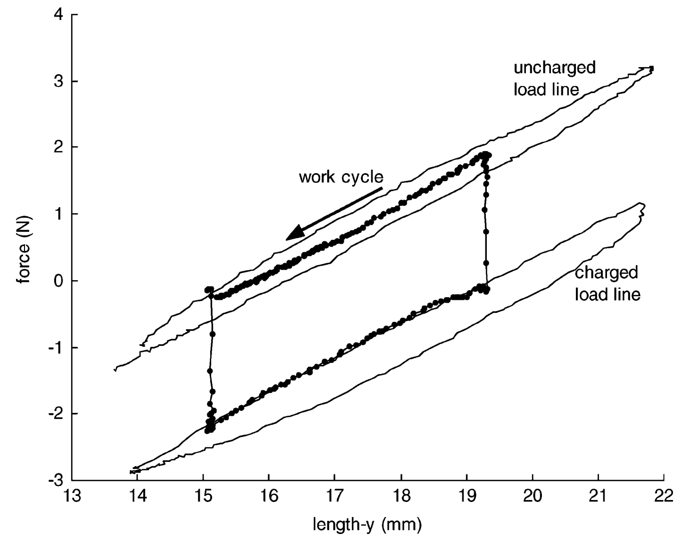


Fig. 7. Experimental force–displacement curves for DE actuator described in Section III-C.

The force–displacement curves in Fig. 7 were recorded by stretching the actuator and returning it to its original state while keeping voltage fixed. Some hysteresis is evident, which is attributed to the viscoelastic losses of the film and frame [21]. The slope of the curve, which corresponds to the stiffness of the actuator, is nearly constant at 0.5 N/mm over the range shown. This suggests that in this particular case, a linear force–displacement model is sufficient to describe the quasi-static elastic behavior of the module

$$F_{\text{elastic}} = k(y - y_0) \tag{2}$$

where F_{elastic} is the force exerted by the actuator. The sign convention used here defines force to be positive when the actuator is under tension. The difference $(y - y_0)$ is the extension of the actuator. The equilibrium length of the actuator is y_0. The spring constant k is a function of the properties and geometries of both the film and its frame.

Fig. 7 shows that changing the voltage from 0 to 5.5 kV offsets the force–displacement curve, but not its slope. Hence the actuator stiffness is constant and independent of the voltage applied over the range shown.

Application of a voltage across electrodes generates a pressure as predicted in (1). Through the mechanics of the film, this pressure is transformed into a relaxation of pressure on the inside of the frame. The force interactions are complex and change with the frame geometry; however, the effect of applying a voltage can be lumped into an effective force (δF) acting to extend the frame in the y direction (see Fig. 8). This force is sometimes referred to as the isometric or blocked force and is equivalent to the change in force a constrained actuator can produce [14]. In Fig. 7, the isometric force is the vertical separation of the charged and uncharged stiffness curves. For the range of motion measured, the isometric force is approximately constant, i.e., the two curves are parallel. Therefore, in a quasi-static spring model, actuation can be represented as a force that is added to stretch the spring, as shown in Fig. 8. The force–displacement

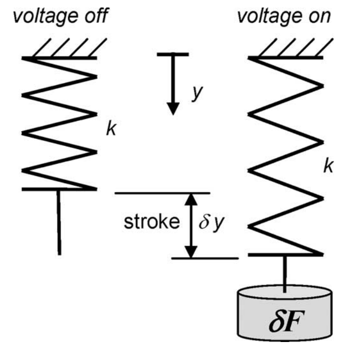


Fig. 8. Quasi-static actuator model. (a) Voltage off. (b) Voltage on.

behavior of the actuated module is then given by

$$F = F_{\text{elastic}} - \delta F. \tag{3}$$

The horizontal separation of the curves in Fig. 7 at a given force corresponds to the actuator stroke (δy), which is independent of external loading, provided the load remains constant throughout the stroke. It is given by

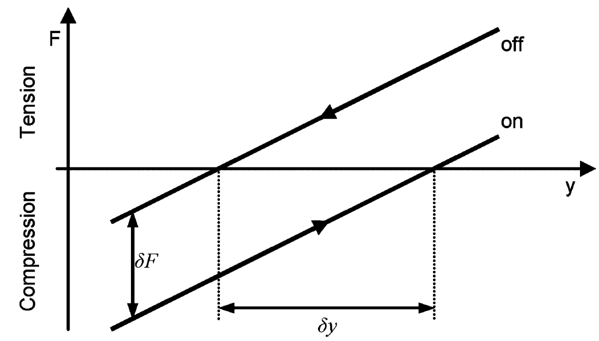
$$\delta y = \delta F / k. \tag{4}$$

Note that the isometric force (δF) is independent of actuator compliance. The compliance of a DE actuator does not prevent producing high isometric forces. Actuator compliance does, however, determine the maximum stroke that can be achieved for a given isometric force, i.e., actuators that can produce large displacements will be inherently compliant.

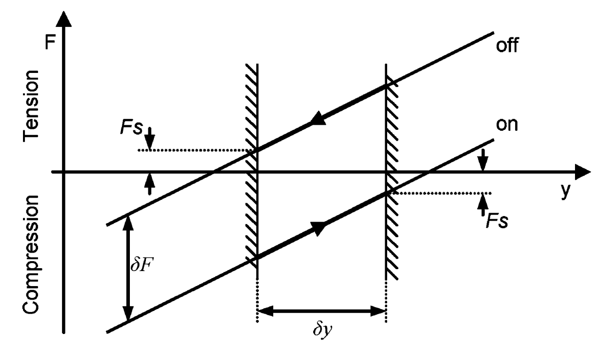
Though simple, the lumped-parameter spring model shown in Fig. 8 describes measured actuator performance well. It is used to illustrate the behavior and further improve the performance of the actuator module. Fig. 9 shows an idealized representation of the force–displacement behavior. Applying a voltage to a constrained actuator will cause it to produce a force equal to the isometric force (δF). When the constraint is removed, the system will expand to a new equilibrium position, with force diminishing linearly as the actuator expands. The usable external force produced by the actuator is not uniform throughout the stroke.

One of the goals of this work is to confirm that DE actuators are effective for binary mechatronic devices, i.e., they provide repeatable motion independent of loading. This can be achieved by driving the actuators from one hard stop to another with a force that exceeds any anticipated load. Fig. 9(b) shows the actuator characteristics after the stroke has been limited by hard stops. The actuator presses against these stops with a force F_s and will hold a constant position if the external loading does not exceed F_s. Such a design is analogous to a pneumatic actuator that is driven to the end of its stroke.

Such an actuator design is not ideal, however. The actuator stroke (δy) has been reduced and the actuator force beyond F_s is not utilized. Such an implementation does not make full use of the actuator capabilities.



(a)



(b)

Fig. 9. Idealized force–displacement behavior of DE actuator. (a) Unconstrained actuator. (b) Actuator with hard mechanical stops.

E. Passive Stiffness Compensation

To produce displacement, the isometric force must overcome the stiffness of the module. According to (4), the stroke is inversely proportional to the stiffness. Reducing the effective stiffness of the module would therefore increase actuator stroke. The stiffness of two springs acting in parallel can be represented by a single spring whose spring constant is the sum of the two individual spring constants, i.e., $k_e = k_1 + k_2$.

Fig. 10(a) shows an idealized representation of the force–displacement profile for a compensated module, before and after actuation. Here, a passive element (yet to be determined) is added in parallel with the actuator module in such a way that the stiffness of the combined system is zero over an operating range. As before, the curves are vertically separated by the amount of the isometric force. By adding hard stops, as illustrated in Fig. 10(b), the range of motion can be limited to the constant stiffness region, and the actuator is made insensitive to disturbance forces when at the end of its range of motion. Both the stroke (δy) and the actuator force (F_s) have increased compared to the uncompensated case [Fig. 9(b)]. The theoretical maximum actuation force F_s is $\delta F/2$. If a passive element was designed that could cancel the actuator stiffness over an arbitrarily large range, the theoretical maximum stroke (δy) is unlimited for this idealized model.

F. Linear Bistable Element (LBE)

The goal is therefore to design a passive element with a negative stiffness to cancel the positive stiffness of the module.

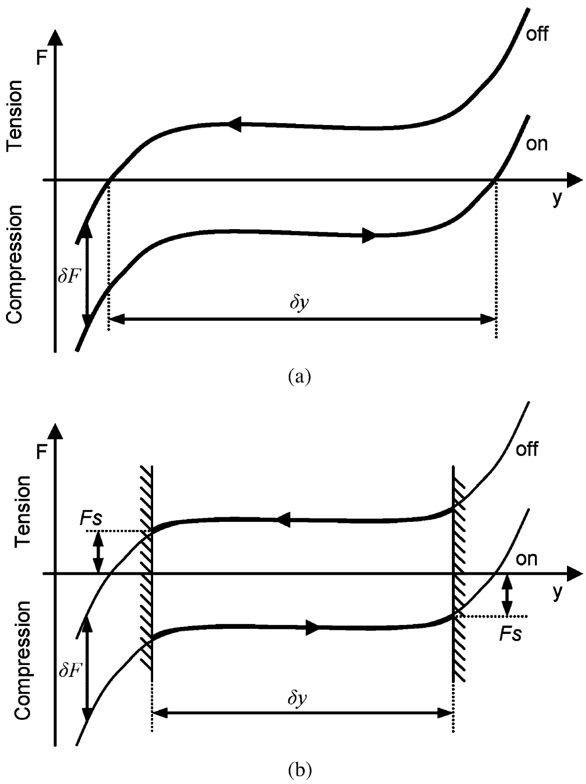


Fig. 10. Idealized force–displacement behavior of DE actuator: (a) with stiffness compensation; (b) with stiffness compensation and hard mechanical stops.

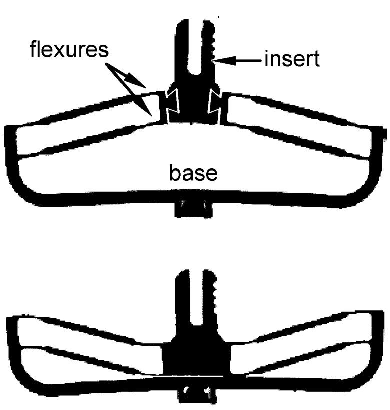


Fig. 11. LBE prototype in its two stable states (interface between insert and base highlighted for clarity).

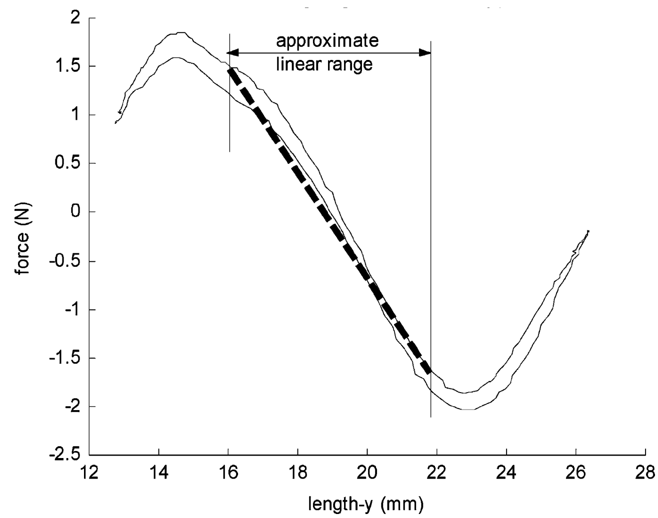


Fig. 12. LBE experimental force–displacement behavior between the two stable states.

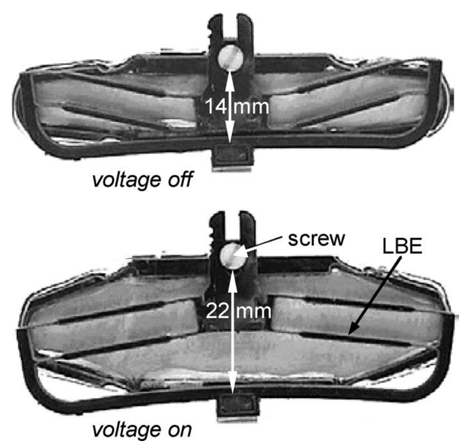


Fig. 13. Compensated actuator prototype at ends of its stroke.

A bistable element is one such element that exhibits a negative stiffness over part of its range of motion. Fig. 11 shows a LBE in its two stable states. It consists of a base that elastically supports two opposing flexure linkages. A slightly oversized insert is placed between the arms, which preloads the base and gives the assembly two stable configurations. In studies here, the LBE base and inserts were each machined from a single piece of Delrin.

The measured force–displacement profile of the LBE is shown in Fig. 12. Part of the curve exhibits an approximately linear region with a slope of –0.5 N/mm. This region is of interest for achieving a zero-stiffness actuator module.

Fig. 13 shows an actuator module integrated with the LBE. The actuator stroke has increased from 4 to 8 mm. Fig. 14 shows the corresponding work cycle. It can be seen that the actuator force is approximately constant over the range that corresponds to zero module stiffness.

G. Antagonistic Actuator Pairs

DE materials behave approximately like electrical capacitors, which ideally draw no current at steady state. (In contrast, an electric motor behaves as an inductive element and draws high stall currents.) In practice, a DE actuator will actually draw a small "leakage" current in steady state. This leakage can be avoided, however, by using antagonistic pairs of modules and using bistable elements to maintain the state of the pair. With this design, voltage is applied only when changing the state of

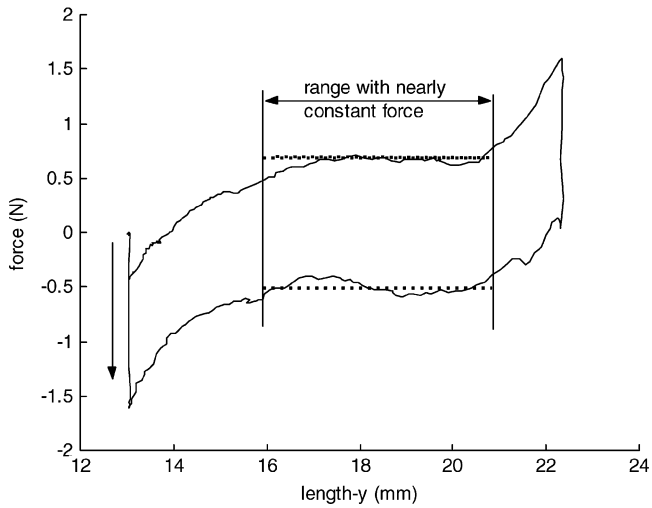
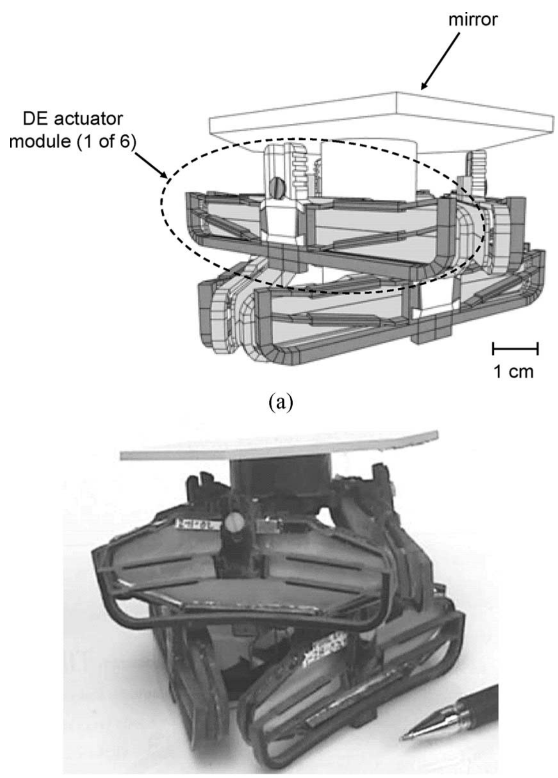


Fig. 14. Compensated actuator force–displacement behavior.



(a)

(b)

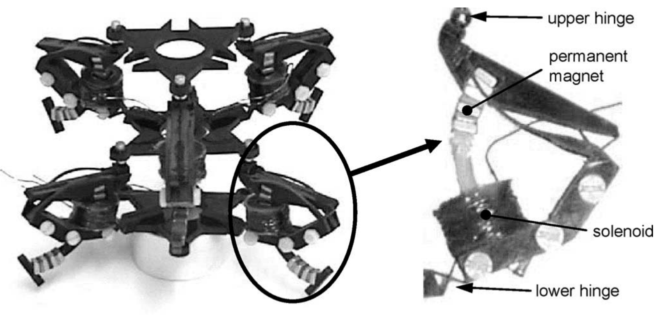
Fig. 15. 6-DoF DE-actuated prototype device. (a) Illustration. (b) Photograph.

the actuator system. Such a design also tends to decrease fatigue and creep in the actuator materials.

IV. Representative Bistable Device Design

A. Design

To demonstrate the potential of DE actuators in binary mechatronic systems, a 6-DoF prototype was designed, fabricated, and tested. Fig. 15 shows the prototype manipulating a mirror. The manipulator can achieve $2^6 = 64$ discrete states or positions. It consists of two stages, each containing three actuators arranged in parallel (see Fig. 1). The prototype device is almost entirely plastic, with a total mass of 74 g. The actuator modules contribute 58 g to this total. The elastomer film and electrodes account for only 1.2 g, which is about 2% of the manipulator mass. The force capabilities of the actuators could thus be increased by using multiple layers of film and electrodes without significantly increasing system mass. While conceptually simple, layering poses technical challenges that are addressed in recent research [29].



(a) (b)

Fig. 16. 6-DoF electromagnet-actuated prototype device. (a) Overall system. (b) Detailed view of actuator.

An actuator in this system takes approximately 3 s to change binary states, and requires no waiting period before it can be actuated again. The time-domain step response closely follows that of an overdamped second-order system, with speed of response largely dependent on the elastomer used for the film. Here, VHB 4910 acrylic was chosen based on its availability, low cost, and relative insensitivity to the simple fabrication techniques used in our laboratory. The drawback of this material is that it is moderately viscoelastic, which limits its response speed [29]. Many other DE materials are less viscous and therefore can be actuated at much higher rates. For example, silicone-based materials have been used to achieve actuation bandwidths in the acoustic range [12]. The actuation speed achieved in this system should not be viewed as a fundamental limitation of the DE actuation concept or the mechanical design presented here, but rather a tradeoff the authors accepted for fabrication convenience.

B. Experimental System Performance

The performance of this system was compared to an electromagnetically actuated prototype, shown in Fig. 16 [9]. With the exception of the actuators, the two devices are quite similar, allowing a meaningful comparison of the two actuator technologies to be made. Neither of the two prototype actuators represents the performance limit of its respective technology, but rather provides a snapshot of the performance achieved in a practical application, given approximately equal development time. It should be noted that the cost of the electromagnetic device was many times the cost of the DE-actuated device.

It is most meaningful to compare the electromagnetic actuator leg shown in Fig. 16(b) to the DE module shown in Fig. 13(a), as they serve the same function when integrated into their respective structures. Forces for the magnetic actuator were measured

TABLE I
COMPARISON OF DE AND ELECTROMAGNETIC ACTUATORS

	Electromagnetic	**Dielectric Elastomer**
Max isometric force (N)	1.5N	1.5N
Work per cycle (mJ)	15mJ	15mJ
Mass of actuator system	20.0g	9.2g
Work per cycle per mass	0.8J/kg	1.6J/kg
Comparison based on active components only		
Mass of actuator active components	14g	0.20g
Work per cycle per active mass	1.1J/kg	75J/kg

as the linear output between the hinges. For both types of actuators, the work per cycle was computed by computing the area within the work-cycle curve. Both actuators produce similar forces and energy output, but differ in mass, with the DE module weighing only half that of its electromagnetic counterpart. The performance of the two actuators is compared in Table I.

In both cases, a substantial fraction of mass comes from the supporting structure. As described above, the DE material is incorporated into the frame and tuned with an LBE so that it can effectively actuate the device. Similarly, the electromagnetic actuator also requires its supporting structure for proper functioning. For the electromagnetic actuator, the active components consist of the solenoid and the magnet, having a mass of 14 g. In comparison, the dielectric film and electrodes making up the active components of the DE actuator have a mass of only 0.2 g. As summarized in the lower part of Table I, the DE material achieves about 70 times the specific energy output per cycle as the solenoid and magnet. Using multilayer methods could improve energy densities further. However, a detailed discussion of these methods is beyond the scope of this paper [29].

V. CONCLUSION

DE actuators have been discussed as a potential enabling technology for very large DoF binary robotic and mechatronic systems. To date, the limitation of DE materials has not been their lack of theoretical performance, but the difficulty of implementing these materials in practical systems. By embedding the film in a flexible frame, an actuator module is formed that can be integrated directly into mechanical systems. The inherent compliance of the DE actuator is addressed by using a passive bistable element to drive the actuator against hard stops, allowing it to accurately maintain one of the two binary states even in the presence of disturbance forces. The force profile of the actuator can be tuned further by incorporating passive elastic elements into the module frame. This actuator design was implemented in an experimental system and demonstrated significantly higher performance than an electromagnetic version having similar design parameters.

The performance of DE actuators shows promise of making large DoF binary mechatronic systems practical, particularly with recent developments in multilayered designs [29]. The simplicity of the actuation mechanism and the use of conventional materials could yield low production cost and enable the large quantities of actuators required for binary mechatronic systems. Ultimately, the simplicity of the actuators along with their effective performance when used in a binary fashion could allow for a new class of robotic and mechatronic devices that are inexpensive, lightweight, and easy to control.

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