Development of a Polymer-Actuated Binary Manipulator

by

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ABSTRACT

Proposed applications for future robotic systems, ranging from space exploration to medical tasks, will require robotic devices and components that are simple, robust, lightweight, inexpensive, and easy to control. Binary actuation greatly reduces complexity by having only two discrete states for each degree of freedom. A high number of binary actuators is required for a manipulator to approach the performance of continuous systems. The complexity of current actuator technology prevents the development of practical binary robots. Dielectric elastomer actuators exhibit high energy densities and large displacement responses and might enable practical binary robots. These actuators exhibit muscle-like behavior and change their geometry as a voltage is applied.

This thesis discusses the application of dielectric elastomer actuators to mechanical system with a special focus on binary robots. The performance of most dielectric elastomer actuators in practical systems is much less than what can be achieved under ideal laboratory conditions. It is shown that good performance is achieved by incorporating the dielectric elastomer into a flexible frame that provides an elastic restoring force. This actuator module can work under both tension and compression. Based on a physical model, the actuator module is tuned with passive elastic elements to have optimal work output when integrated into a mechanical system. These actuator modules are used to power a binary manipulator. A six degree of freedom prototype demonstrates feasibility.

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Chapter

1

Introduction

This thesis reports on the development of a high-degree of freedom binary manipulator powered by dielectric elastomer actuators. Binary actuation could advance the field of robotics much the way digital circuitry revolutionized computing. Binary actuation greatly simplifies design as each degree of freedom has only two discrete states and therefore does not need feedback control. A large number of binary actuators is required to approach the performance of continuous systems [Chirikjian, 1994; Lichter 2001]. The complexity of conventional actuator technology prevents the development of practical hyper redundant binary robots.

Dielectric polymer actuators exhibit high energy densities and large displacement responses. Because of their fundamental simplicity and light weight they show promise of making high DOF binary systems feasible. These actuators belong to the class of electroactive polymers (EAPs), which exhibit muscle like behavior and change their geometry as a voltage is applied.

Both dielectric elastomer actuators and the concept of binary robotics have and studied independently. The goal of this research was to merge these two technologies. The research focused on developing artificial muscle-based actuator modules to power a binary manipulator. The design and performance of these modules is presented in detail. A prototype of a binary six degree of freedom manipulator demonstrates feasibility of this concept.

1.1 Motivation

This thesis presents a contribution to a cooperative research program on Self-Transforming Robotic Planetary Explorers at the MIT Field and Space Robotic Laboratory (FSRL). The program was funded by the NASA Institute for Advanced
Concepts (NIAC), an agency created to promote research that may significantly impact the aerospace community in the next 10 to 40 years. [NASA Institute for Advanced Concepts, 2002].

An important objective of the international space science community is the exploration of planets and moons of our solar system [NASA, 1998]. This will require robotic systems capable of constructing facilities and performing challenging science tasks in an unstructured environment. Current fixed geometry rovers are too limited in their capabilities. A new class of robots is required to meet the needs of future missions [Dubowsky, 1999]. As part of the NIAC the concept of a self-transforming planetary explorer (STX) was developed [Andrews, 2000]. Such a system would be able to adapt its configuration to overcome a wide range of obstacles and perform a wide range of tasks. Such a system cannot be realized with conventional components, such as motors, gears, bearings, cables, and connectors. Instead, compliant members with embedded actuation, sensing, power, and communication networks have been proposed [Dubowsky, 1999; Andrews, 2000]. By actuating these members in a binary fashion, much like electronics, they benefit from the fault tolerance of having only two states [Chirikjian, 1994].

In the NIAC study, binary manipulators with applications to space systems were studied in computer simulations. Algorithms were developed for solving the forward and inverse kinematics [Lichter 2001, Lichter et al. 2002]. It was found that a binary manipulator with about 50 binary degrees of freedom could perform some simple tasks. Figure 1.1 illustrates some example applications for maneuvering an instrument and for six-legged locomotion. These theoretical results are very encouraging to the field of binary robots as they suggests that the computational requirements are reasonable and the inverse kinematics for trajectory following and locomotion planning could be done in real time [Lichter 2001, Lichter et al. 2002].

Several enabling technologies for the STX where considered. A lightweight, hyper redundant deployable manipulator called the Binary Robotic Articulated Intelligent Device (BRAID) was developed to demonstrate key enabling technologies for an STX [Sujan et al., 2001]. A single stage of a first generation BRAID design is shown in
Figure 1.2a. It is a three degree of freedom compliant mechanism with embedded actuators. Flexures are used to replace conventional bearings. The joints are actuated by two-state shape memory alloys (SMAs). The first generation BRAID prototype (BRAID I) has 15 degrees of freedom and is shown in Figure 1.2b in its undeployed state [Sujan et al., 2001].

![Figure 1.2a. It is a three degree of freedom compliant mechanism with embedded actuators. Flexures are used to replace conventional bearings. The joints are actuated by two-state shape memory alloys (SMAs). The first generation BRAID prototype (BRAID I) has 15 degrees of freedom and is shown in Figure 1.2b in its undeployed state [Sujan et al., 2001].](image)

Figure 1.1. Application of binary manipulators to planetary exploration (Matt Lichter, 2001)

![Figure 1.1. Application of binary manipulators to planetary exploration (Matt Lichter, 2001)](image)

![Figure 1.2. First BRAID prototype (Vivec Sujan, 2000)](image)

![Figure 1.2. First BRAID prototype (Vivec Sujan, 2000)](image)
A second generation BRAID (BRAID II) was developed that incorporated bi-stable elements to improve repeatability, see Figure 1.3 [Hafez et al., 2002]. It was actuated by electromagnets. In contrast to the shape memory alloys, by controlling the direction of current through the electromagnet, the forces and thus motions could be achieved in two directions with a single actuator. Bi-stable elements allowed a joint to repeatably reach and maintain each of its two states. This greatly reduces power consumption as electrical input is only required for a short time to move a joint from one state to another.

The two prototypes achieved moderate performance and were successful in demonstrating some of the concepts important for enabling binary robotics. The main limitation of both prototypes was the actuator performance. The SMAs are relatively slow, exhibit expansions of about 5%, and are sensitive to the thermal environment. The electromagnetic actuators were heavy and limited the number of stages of the BRAID to two. The electromagnetic prototype confirms the belief that conventional actuator technology is too heavy and complex to make high degree of freedom binary system practical.
There is therefore a need to develop actuators technologies that can overcome these limitations. The objective of this research was to demonstrate that dielectric polymer actuators have the potential of making binary robotics practical.

The need for binary robots does not only exist in planetary explorers. Applications for robots include manufacturing, assistance in medical procedures, household and mobility aids, and entertainment. In general, all these applications share the need for robotic systems and components that are effective, inexpensive, lightweight, and easy to control. The key enabling technology to achieve such systems discussed here is artificial muscle-based binary actuation.

1.2 Background and Literature

1.2.1 Binary Manipulators

In the 1960's and 70's the concept of binary robotics was introduced [Anderson et al., 1967; Roth et al., 1973]. In the last ten years increased computation power made the analysis, control and planning of binary robots with a large number of degrees of freedom feasible [Chirikjian, 1994; Chirikjian, Ebert-Upoff, 1994; Lees, Chirikjian, 1996]. The planning and control of binary manipulators is fundamentally different from their continuous low DOF counterparts. For example, the inverse kinematics problem for a binary device requires a search through a discrete set of configurations. For a high DOF binary manipulator, exhaustive searches of the work space can become impractical. Combinatorial search algorithm and genetic algorithms have led to a dramatic reduction of computation time [Lees, Chirikjian, 1996; Lichter, 2001].

Some experimental work has been done on redundant manipulators. An example is a large variable geometry truss (VGT) manipulator that was constructed using pneumatic actuators. Binary action was achieved with two mechanical constraints and driving the actuator against the constraints [Chirikjian, 1994]. An example of a highly redundant manipulator is a 30 degree of freedom snake-like VGT structure, which uses D.C. servo motors and lead screw drives. Its motion was constrained to the horizontal plane [Chirikjian, Burdick, 1994]. These implementations, while acceptable for systems with few DOF, cannot readily be extended to develop practical systems with very large...
DOF. To date, little work has been done to develop simple, lightweight robust binary design concepts.

1.2.2 Actuator Technologies

Shape memory alloys actuate in response to a temperature change. They achieve motion by the reversible solid state phase transformation, known as the martensitic transformation. The two phases have a different density and are a function of the material temperature [Waram 1993]. In their simplest form, SMAs come in the form of wires that contract in response to electric heating. The cycle time is limited by the thermal response of the material. They generally reach strains of less than 5%, and achieve pressures beyond 200MPa [Pelrine et al., 2001].

Piezoelectric actuators are ceramic or polymer-based and change their shape in response to an electric field. A simplified model of the piezoelectric effect is to consider the anions and cations forming a crystal lattice to be connected by springs. Under an applied electric field, the anions and cations will want to move in opposite directions, and thereby cause a deformation of the crystal lattice [Hunter, Lafontaine, 1992]. Piezoelectric actuators have fast response rates, achieve high pressures over 100MPa, but relatively small strains, generally less than 1% [Pelrine et al., 2001]. Compliant mechanisms have been proposed to amplify the motion of small strain actuators [Kota et al., 1999].

Electro active polymers (EAPs) form a diverse group of polymer-based actuators that produce a mechanical response to electrical stimulation. Conducting polymers achieve volume changes by the insertion and removal of ions. This occurs as a result of oxidation and reduction reactions, which can be controlled electrically or chemically. The polymer has to be in contact with an electrolyte, which in general is liquid based. This currently limits the range of applications of conduction polymers, even though they achieve strains up to 10% and pressures up to 450Mpa [Baughman 1996; Madden et al., 1995; Madden et al., 2000] Polymer gels containing a dielectric solvent swell as a result of an applied voltage [Bar-Cohen, 2001].

The actuator technology applied to binary robots during this research is dielectric elastomer actuators. The operating principle is simple and shown in Figure 1.4. An
elastomeric dielectric film is coated on both sides with compliant electrodes. As a voltage is applied to the electrodes, electrostatic (Maxwell) stresses cause the film to compress in thickness and expand in area. This area expansion can be used to actuate mechanical systems [Pelrine et al., 1997; Pelrine et al., 1998; Kornbluh et al., 1999].

![Diagram of dielectric elastomer actuator](image)

**Figure 1.4. Dielectric elastomer actuator operating principle (Figure adapted from SRI International [Pelrine et al., 1997])**

The Stanford Research Institute (SRI) International has started developing dielectric elastomer actuators in 1992 [Pelrine et al., 1997, 1998, 2000, 2001; Kornbluh et al., 1999, 2001, 2002]. In recent years improved performance has been achieved with the identifications of new elastomer materials. This led other researchers in the US [Liu et al., 1999], at the Riso National Laboratory of Denmark [Kofod et al., 2001; Sommer-Larsen et al., 2001], and at Sungkyunkwan University of Korea [Cho et al., 2001; Jeon et al., 2001] to perform active research on dielectric elastomer actuator in addition to the FSRL.

The basic operating principle is well understood and has been verified experimentally. Actuator response can be predicted accurately for small strains, but predicting becomes more difficult at large strains due to the non-linear elastic properties of the polymers [Kornbluh et al., 1999]. An acrylic and a silicone elastomer have been characterized extensively and have been described by large strain elasticity models. Systematic experiments have been performed on an actuator to measure isometric force and strain under varying amounts of stretching of the acrylic and silicone elastomers.
Characterization of the electrical and mechanical polymer properties is an ongoing effort. [Sommer-Larsen et al., 2001].

Dielectric elastomers have been proposed for use in linear actuators, loudspeakers, solid state optical devices, and as generators [Heydt et al., 1998; Pelrine et al., 2001]. A variety of geometric configurations convert the area expansion of the film to linear motion. For example, the actuator film can be constrained in planar frames or be rolled into tubes that change length. For these cases, the direction of the actuator motion is in the same plane as the film expansion [Pelrine et. al. 2001]. An example of an out-of-plane device is a cone-shaped actuator, in which the motion is normal to the undeformed film [Cho et al., 2001].

Planar geometries of dielectric polymer actuators have been proposed to power a snake-like manipulator and an insect-inspired hexapedal walker [Eckerle et al., 2001; Pelrine et al., 2001]. A conical geometry has been proposed to power an inchworm robot [Cho et al., 2001]. Since the actuators only work in tension, some external restoring force is required, which can be achieved in a variety of ways. For the case of the snake-like manipulator, each degree of freedom is controlled by an antagonistic pair of actuators. The hexapedal walker and the inchworm robot use return springs to provide the restoring force [Eckerle et al., 2001; Cho et al., 2001]. Combining an actuator with a mechanism with a negative spring constant to increase the range of motion has been proposed. An over-center mechanism has been demonstrated to increase the range of motion of a silicone actuator by a factor of five [Pelrine et al., 2000]. Position feedback provided by a laser displacement sensor has been used to control a dielectric elastomer actuator [Jeon et al., 2001].

The above actuator technologies are often referred to as artificial muscles. While literature does not seem to provide a consensus for an exact definition for an artificial muscle, in the most general terms it refers to an actuator that exhibit muscle-like behavior. That is, it is a material that provides some mechanical response to an electrical stimulus [Bar-Cohen, 2001]. A more narrow definition would be to only consider materials whose performance is largely independent of scale. A large actuator could then be considered as a combination of many small ones [Pelrine et al., 2000]. Aside from
manufacturing limitations, these materials can function on a very small scale. This is in contrast to electric motors and hydraulic actuators, whose efficiency increases with size.

Researchers quantify the actuator performance using parameters including strain, stress, speed, energy density, power density, and efficiency. Despite an abundance of published values, care must be taken in numerically comparing the various actuator technologies. Not a single procedural standard for measuring these parameters has been adopted. Also, the reported values are generally achieved under ideal conditions and tend to be less in real life situations [Meijer et al., 2001].

Nevertheless, there are good reasons to justify the choice of dielectric elastomer actuators for binary robots. In contrast to SMAs and conducting polymers, dielectric elastomer actuators achieve very large strains, with up to 380% being reported [Pelrine et al., 2001]. The stress and strain properties allow them to be implemented in a “direct drive” fashion, simplifying robot design by eliminating the need for motion amplification. They have also shown good performance in terms of energy density, efficiency and actuation speed [Pelrine et al., 2001]. They can be made from common materials and are inexpensive.

1.3 Research Overview

Both dielectric elastomer actuators and the concepts of binary robots have been studied independently. The objective of the research is to merge these two technologies to allow for the development of practical, lightweight, inexpensive, and easy to control robots. A conceptual representation is shown in Figure 1.5. The BRAID is used as a platform to demonstrate some of the key enabling technologies believed important to future robots. A third generation BRAID was developed that features dielectric elastomer actuators.

Chapter 2 describes the development of binary actuator modules. Under laboratory conditions dielectric elastomer actuators have achieved very high energy densities, exceeding those of conventional technologies such as electromagnets [Pelrine et al., 2001]. To date, the performance of these actuators when applied to practical devices is less than what can be achieved under ideal conditions [Meijer et al., 2001]. Research was performed on how to best exploit the performance of the dielectric
elastomers in practical systems. While the literature describes some prototype devices, little research has been performed on how to best implement these actuators. In this context, implementation refers to the way in which the actuator is integrated into a system. For example, an electric motor interacts with a mechanism mainly through torques and rotational displacement transmitted by the motor shaft. The maximum energy output will occur if the motor impedance matches that of the system [Kornbluh et al., 2001]. For the case of the dielectric elastomers, the interaction between the actuator and the systems involves many variables and is therefore more complex. Upon actuation, the actuator changes shape and along with it the boundary conditions on actuator material, which is turn affects the mechanical and electrical properties of the actuator. In the area of dielectric elastomer actuators, the key contribution of this research is the development of an actuator module that can work under both tension and compression with a constant force throughout its stroke.

Chapter 3 describes the BRAID design that incorporates the actuator modules. The current and projected kinematic performances are presented.

Figure 1.5. Polymer-actuated binary manipulator
Chapter 2

Actuator Module Design

The chapter presents the development of a self-contained actuator module, which behaves as a mechanism with embedded actuation. The underlying physics of a dielectric elastomer actuator are briefly reviewed and then applied to a linear actuator. Based on this model, the actuator is tuned to achieve performance appropriate for binary robots.

2.1 Actuator Basics

2.1.1 Operating Principle

The dielectric polymer that separates the electrodes experiences an electrostatic pressure, or Maxwell stress, as a charge is applied to the electrodes. Two force components contribute to the deformation of the elastomeric film. The unlike charges on the opposing electrodes attract each other and generate a compressive stress in the $z$-direction on the film. The repulsion of like charges on the same electrodes generates shear stress in the planar (x and y) directions of the film, see Figure 2.1 [Pelrine et al., 1998].

![Figure 2.1. Electrostatic forces acting on polymer film](image)

The compressive and tensile components of the stress are coupled by the constant volume property of the film, which is given by

$$\left(1 + s_x\right)\left(1 + s_y\right)\left(1 + s_z\right) = 1.$$  \hfill (2.1)
where $s_x$, $s_y$, and $s_z$ are the strains in three directions. For example, the strain in the $y$-direction is defined as

$$s_y = \frac{y}{y_0} - 1,$$

(2.2)

where $y_0$ is the original length. The contributions by the compressive and shear stresses can be lumped into a single effective pressure ($p$), which is given by

$$p = \varepsilon \varepsilon_0 E^2 = \varepsilon \varepsilon_0 \left( \frac{V}{z} \right)^2,$$

(2.3)

where $\varepsilon$ is the relative dielectric constant, $\varepsilon_0$ is the permittivity of free space ($\varepsilon_0=8.85\times10^{-12}\text{F/m}$), and $E$ is the applied electric field, which is the ratio of the applied voltage ($V$) over the film thickness ($z$) [Pelrine et al., 1998].

If the film is perfectly elastic, the effective pressure can be related to the thickness strain ($s_z$), which is given by

$$s_z = -\frac{p}{Y} = -\frac{\varepsilon \varepsilon_0 E^2}{Y} = -\frac{\varepsilon \varepsilon_0}{Y} \left( \frac{V}{z} \right)^2,$$

(2.4)

where $Y$ is the young's modulus of the elastomer [Pelrine et al., 1998]. This equation is accurate for small strains, i.e. when the thickness ($z$) is close to the original thickness ($z_0$), and the elastic behavior is in the linear range. Typically, the expansions in the planar directions are of more interest. The planar area strain ($s_a$) can be derived from Equation 2.1 (where $(1+s_a)=(1+s_x)(1+s_y)$) and is given by

$$s_a = \frac{1}{1+s_z} - 1 = \frac{1}{1 - \frac{p}{Y}} - 1 = -\frac{p}{Y - p}.$$

(2.5)

2.1.2 Fixed Frame Actuators

Figure 2.2 shows a simple yet effective test setup for demonstrating and evaluating performance of various actuator materials [Kornbluh et al., 1999]. A polymer film, such as silicone, is stretched over a rigid frame so that is has a final thickness ($z_0$) of about 0.1mm. Circular electrodes are applied at the center and on both sides of the film by using a stencil and brushing on conductive grease. A narrow trace of grease leads from each electrodes to the edge of the frame for electrical connection. Applying a
voltage on the order of 5kV causes the film to compress in thickness and expand in area. As Equation 2.4 predicts, increasing the voltage will cause greater strains. However, eventually the film will breakdown causing the electrodes to short out and destroy the film.

In the subsequent discussion, the region of polymer sandwiched between electrodes will be referred to as active film or active region. Similarly, the area that is free of electrodes will be referred to as the inactive film or region. For this experiment, the electrode diameter has to be significantly less than the inner diameter of the frame to minimize the effects of the boundary constraints. The area strain is easily measured by monitoring the size of the electrode. It is more difficult to measure thickness strain. However, it can be calculated from the area strain, assuming the constant volume property of Equation 2.1. The applied voltage can be monitored with a standard multimeter through a voltage divider.

Such a setup has been used by SRI to experimentally verify Equation 2.5, which relates planar expansion to the applied voltage. Close agreement between experimental and analytical results are reported for thickness strains ($s_t$) up to 15% [Kornbluh et al., 1999].

![Figure 2.2. Test setup to evaluate actuator performance](image)

The first dielectric polymer actuators built at the FSRL looked similar to the one in Figure 2.2. Initially, a procedure outlined by an online “recipe for an artificial muscle,” maintained by SRI, was followed [SRI International, 2000]. The initial challenges were manufacturing uniform silicone film that didn’t break down prematurely.
due to material imperfections. Significant improvements were finally achieved by using a commercially available acrylic polymer and by pre-stretching the film.

Figure 2.3 shows an actuator undergoing an area strain (\(s_a\)) of over 100% upon applying a voltage of 6.5kV. In the given example the original film thickness is \(z_0=80\mu m\), which reduces to \(z_1=39\mu m\).

![Figure 2.3. Planar expansion of a dielectric polymer actuator sample](image)

2.1.3 Elastomeric Films

The key component of the actuator is the polymer elastomeric film, which controls many of the actuator properties. Polymers are generally obtained by forming organic molecules into gigantic molecular chains. The bonding in the chains is covalent, and the chains are held together by entanglement and weak secondary bonds. Elastomers have highly coiled and partly cross-linked chains, which allows for large elastic deformation. When a stress is applied to most polymers, both elastic and plastic deformation occur. The elastic deformation is due to the stretching of the covalent bonds within the chains and can be recovered. Plastic deformation is due to the sliding and disentangling of the polymer chains and cannot be recovered. This flow of polymer chains relative to each other is viscous and therefore time dependant. A consequence of the viscoelastic property is creep, which means a constant load will cause a polymer to continue to stretch over time. A second consequence is stress relaxation, which refers to the decrease of stress over time in a stretched sample. These properties are highly temperature dependant and vary greatly between polymers [Askeland, 1994].
A variety of elastomers has been evaluated for use as dielectric actuators including acrylic polymers, silicone, polyurethane, and natural rubber latex [Kornbluh et al., 1998]. During this research acrylic and silicone polymer films where used. These had shown great strain responses and high energy densities [Pelrine et al., 2000].

The acrylic polymer is VHB™ 4910 (Very High Bond) made by 3M™. It is sold as an adhesive tape and is available in film form with a zero-strain thickness of 1mm. It is a clear and very elastic material that can be stretched by 5 times its length in both planar directions without tearing. As its name implies, it is very sticky, which in many ways facilitates actuator assembly as it can be easily bonded to other components without the need of additional adhesive. However, accidental contact of the film with other parts can cause bonds so strong that they cannot be separated without destroying the film. The acrylic elastomer is made of mixtures of aliphatic acrylate. This material has demonstrated the largest energy densities and strains when used as dielectric elastomer actuator [Pelrine et al., 2000]. The good performance is made possible by the high dielectric strength, discussed in more detail in Section 2.1.4. The maximum linear strain that has been achieved under actuation at the FSRL is 240%. The acrylic does, however, have relatively high viscoelastic losses. If subject to pressure it will creep over time. The viscous losses limit the efficiency as some energy is converted to heat. The viscous behavior also limits the speed of response. When used as an actuator, the material exhibits a significant amount of hysteresis at high speeds. The viscosity can be useful in damping vibrations of a manipulator.

The silicone is based on a polydimethyl siloxane backbone. The silicone based actuators were made from self-leveling GE RTV118. In its uncured state it is fairly runny and spreads outs evenly when placed on a level surface. Films were made by spreading the silicon on an acrylic sheet with a knife blade. Uniform thickness was ensured by attaching to two strips of tape to the level surface to control the separation to the knife blade [SRI International, 2000]. Care has to be taken to avoid imperfections due to air bubbles or foreign particles. In comparison to VHB™ 4910, the silicone exhibits significantly lower viscoelastic losses. The maximum strain that has been achieved at the FSRL using a silicone-based actuator is 60%.
2.1.4 Dielectric Strength

The maximum effective pressure that can be achieved for a given film is given by

\[ p_{\text{max}} = \varepsilon \varepsilon_0 (E_{\text{max}})^2. \]  

(2.6)

where \( E_{\text{max}} \) is the dielectric strength or of the polymer. It is the maximum electric field, or ratio of voltage to thickness \((V/z)\), a dielectric can support without breakdown. If the dielectric strength is exceeded, electrons are pulled away from their atoms and cascade through the material. Electric breakdown of an actuator is accompanied by an electric arc as the stored electrical energy discharges rapidly. Electric breakdown typically renders the actuator useless. Since the dielectric strength \((E_{\text{max}})\) appears as a square in Equation 2.6, it is crucial to the performance of the actuator.

The dielectric strength is a property of the material. For polymers it also varies significantly with pre-stretching, which has been reported by SRI [Pelrine et al., 2000]. A detailed characterization of the VHB\textsuperscript{TM} 4910 polymer has been published by RISO [Kofod et al., 2001]. The dielectric strength is 18MV/m for an undeformed sample and increases to 218MV/m when stretched by 500\% in both planar directions. Pre-stretching VHB\textsuperscript{TM} 4910 increases the maximum attainable effective pressure by more than two orders of magnitudes and is therefore very important to actuator design.

According to Equation 2.6, the maximum stress is independent of film thickness. A thicker film can support higher voltages but the maximum ratio of voltage over thickness \((E_{\text{max}}=V_{\text{max}}/z)\) remains unchanged. In practice it was found that extremely thin silicon films tended to break down at lower electric fields. A possible explanation is that material imperfections reduce the film thickness locally. The absolute size of these imperfections is independent of film thickness and therefore more significant for thinner films.

2.1.5 Capacitance and Dielectricity

Electrically, the dielectric polymer actuator behaves as a capacitor, which in its most basic form consists of a pair of conductors that stores separated charges. The capacitance \((C)\) is defined as

\[ C \equiv \frac{Q}{V}. \]  

(2.7)
where $Q$ is the electric charge. In the case of the dielectric polymer actuators, this charge is stored on the compliant electrodes. The actuator can be modeled as parallel plate capacitor consisting of two conducting plates each of area $A_{xy}$, which are separated by the film thickness ($z$). The capacitance is given by

$$C = \frac{Q}{V} = \varepsilon \varepsilon_0 \frac{A_{xy}}{z}.$$  \hspace{1cm} (2.8)

Since the actuator undergoes a geometry change upon actuation, both the area $A_{xy}$ and distance $z$ vary significantly. The permittivity of free space $\varepsilon_0$ is constant at $8.85 \times 10^{-12} \text{F/m}$. The relative dielectric constant $\varepsilon$ is a function of the material separating the charges. The relative dielectric constant is the increase in capacitance that results when an insulating material is placed between the two conductors. In this context, the insulator is referred to as a dielectric. On the microscopic level, the increase of capacitance arises from the alignment of dipoles in the insulator with the external electric field [Fishbane et al., 1996].

The dielectric constant tends to drop as a polymer film is stretched. A possible explanation is that straining a polymer inhibits the alignment of dipoles with the electric field. VHB™ 4910 experiences a drop of its dielectric constant from about 4.7 to 4.5 as it is stretched from 0% to 400% in both planar directions [Kofod et al., 2001]. While interesting scientifically, this behavior is considered of little significance in actuator design due to its relatively small effect on the maximum attainable effective pressure.

### 2.1.6 Electrodes

Practical electrodes have to meet both electrical and mechanical requirements. Their function is to exert pressure on the elastomeric film, which, however, changes significantly in size. To not interfere with the desired actuator motion, the electrodes have to be compliant, meaning that their effective stiffness should be significantly lower than that of the film. The electrodes further have to maintain their conductivity under large strains.

Several electrode materials have been investigated. Carbon black can be applied onto the film with a brush or cotton swab. However, the amount of carbon black that bonds to the film is limited. Thicker electrodes were achieved by smearing on
conductive carbon grease (Circuit Works 7200) or conductive silver grease (AI Technology Electro-Grease 8501). Experiments that determine how the quantity of electrode material affects actuator performance have not been performed yet.

The electrodes used for this research are functional, but leave room for improvement. The main issue is that the electrodes are messy and rub off easily with incidental contact. More novel electrodes have been reported by RISO. One of them involves combining a powdered conductor with a bonding agent. This mixture is then diluted and sprayed onto the polymer film with an airbrush [Kofod, 2001]. Due to the complexity of this process, it has not been attempted at the FSRL. An interesting observation is that the use of carbon powder for electrodes allows for an electric, yet totally non-metallic actuator.

2.1.7 Electrical Requirements

High voltages on the order of several thousand volts are required to actuate dielectric polymer actuators. This should not be mistaken to mean that the actuator requires enormous high-power electrical supplies. The current drawn is extremely low. Figure 2.4 shows the electrical input to the actuator presented in Figure 2.2. Voltage and current are shown versus time as the actuator is switched on and off.

![Figure 2.4. Input current and voltage to actuator](image-url)
As expected, the current response shows similarities with that of a simple RC circuit. An electrical lumped parameter model that accounts for the observations is shown in Figure 2.5. The capacitance \( C \) is a function of the film geometry, which varies with the applied voltage. The time response plot shows that the current \( I_a \) reaches a steady-state value of about 0.5\( \mu \)A. The dielectric film doesn’t behave as a perfect insulator and allows for a small leakage current \( I_L \) through the dielectric film, which can be modeled as a resistor \( R_L \) in parallel with the capacitor. The electrodes and electrical connections behave as a resistor \( R_e \) and limit the peak currents.

The actuator is switched off by removing the power supply and draining the charge through a resistor \( R_d \). The draining of the actuator is indicated by the negative current in Figure 2.4. Theoretically, the stored electrical energy can be recovered and returned to a battery.

![Figure 2.5. Electrical lumped parameter actuator model](image)

The fact that dielectric polymer actuators have a dominantly capacitive behavior contributes to their efficiency. This is an important distinction to voice coil actuators and electric motors, which exhibit inductive behavior. Such devices draw high stall current and are not efficient when they have to hold a steady load. The only stall current experienced by the dielectric polymer actuator is the small leakage current \( I_L \).

The stored potential energy \( U \) of a capacitor \( C \) with a charge \( Q \) can be predicted analytically and is given by

\[
U = \frac{1}{2} \frac{Q^2}{C} = \frac{1}{2} CV^2. \tag{2.9}
\]
For the case of the actuator film, Equation 2.8 can be substituted for the capacitance \((C)\), and the stored electric energy becomes

\[
U = \frac{1}{2} \frac{\varepsilon \varepsilon_0 A_{xyz}}{z} V^2 = \frac{1}{2} \varepsilon \varepsilon_0 \left( A_{xyz} z \right) E^2. \tag{2.10}
\]

The quantity \(A_{xyz}\) represents the active actuator volume, which remains constant throughout actuation. This result is intuitive, as it predicts the electrical energy to scale proportionally with actuator size.

### 2.2 Power supply

The high voltage requirement is often stated as a disadvantage of dielectric elastomer actuators, but does not present a fundamental problem. High voltage DC to DC converters are commercially available from companies such as EMCO and Matsusada and produce output voltages as high as 30kV [Emco, 2002; Matsusada, 2002]. For low power applications, such as those presented in this research, the DC-DC converters can be made very compact. Emco’s Q101-5 model has an output voltage range from 0 to 10,000V. It is cube-shaped with a length of only 22mm. The gain is fixed at 2000 and the output voltage can be controlled by regulating the input voltage from 0-5V. Figure 2.6a shows the DC-DC converter integrated with support circuitry. The power is provided by a 9V battery. A variable resistor controls the input voltage to the DC-DC converter. For ease of use, all the components where placed inside a plastic box, as shown in Figure 2.6b.

Some applications might require circuitry that directly operates at the high voltage of the actuator. Some electronic components such as capacitors and transistors that can operate at very high voltages are commercially available [Kornbluh et al., 2002]. However, they are currently more expensive than their low-voltage counterparts, which seems to be due to a lack of demand rather than a fundamental technical limitation [Pelrine et al., 2001].
Any conductors carrying these high voltages need to be appropriately insulated or separated sufficiently in space from other conductors. On the other hand, high voltage allows for reasonable resistance of the conducting components such as the power leads electrodes. The low current allows for small leads and does not induce large electromagnetic fields that could interfere with surrounding electronics.

The power requirements during this research were small and the high voltage didn’t pose a significant risk to the operator. As the actuator and power requirements become large, appropriate precautions to have to be taken. Due to its capacitive behavior, the actuator can store electrical energy that can be released almost instantaneously.

Voltage scales proportionally with film thickness for a given electric field. Thus, the required voltage can be reduced by using thinner films. During this research, no such effort was made, since when used as a single layer, thicker films provide higher forces and are easier to work with.

### 2.3 Linear Actuators

#### 2.3.1 Linear Actuator Model

The actuators presented in Section 2.1.2 were unable to perform useful mechanical work. A simple way to produce linear motion with dielectric elastomer actuators is by stretching the film between two parallel beams, as shown in Figure 2.7.
Applying a voltage expands the film and separates the beams. The direction parallel to the output motion is referred to the active direction \((y)\), and the one perpendicular is referred to as the passive direction \((x)\).

![Diagram of linear parallel beam dielectric elastomer actuator](image)

*Figure 2.7. Linear parallel beam dielectric elastomer actuator*

The physical model presented in Section 2.1.1 can be extended to predict the performance of the linear actuator presented in Figure 2.7 [Kornbluh et al., 2001; Kofod 2001]. The actuator aspect ratio will be defined as ratio of the dimensions in the passive to active directions, or

\[
R = \frac{x_0}{y_0}. \tag{2.11}
\]

For simplicity it is assumed that the aspect ratio is large, i.e. \(R \gg 1\). This way, there is negligible pressure gradient and motion in the passive direction, reducing the analysis to a two-dimensional problem. Figure 2.8a shows a cross-section of the linear actuator to which a tensile load is applied. The simplest way of relating force and displacement of an elastic member is by using Hooke’s model:

\[
F = k (y - y_0). \tag{2.12}
\]

The force \(F\) is proportional to the spring constant \(k\) times the deflection of the spring, which is expressed as the difference of the final length \(y\) and the undeformed length \(y_0\). The sign convention adopted here states that a positive external force \((F)\) applies tension to the actuator. The deflection can also be expressed as a function of the strain \(s_y\):

\[
F = k (y_0 s_y). \tag{2.13}
\]
The spring constant of a parallel beam actuator is a function of geometry and the material modulus:

\[ k = \frac{YA_{xz0}}{y_0}, \]  

(2.14)

where \( Y \) is the tensile modulus of the elastomer and \( A_{xz0} \) is the cross-sectional area of the actuator as defined in Figure 2.8a. Since the cross-sectional area \( (A_{yz}) \) decreases as the actuator is stretched, Hooke’s model is only accurate for strains up to 10\% for the acrylic elastomer [Kofod, 2001]. More complex elastic models, such as the Mooney-Rivlin and Odgen models have been shown to fit experimental data for much larger strains [Kofod, 2001]. It is shown later that Hooke’s model is sufficient in describing the actuators presented here, even though they achieve strains that are larger than 10\%.

If the active film is constrained in the passive direction, the effective pressure gets channeled to cause a force in the active direction. This force is given by the actuator cross-sectional area \( (A_{xz}) \) times the effective pressure \( (p) \):

Figure 2.8. Linear parallel beam actuator model
\[ dF = pA_{xz} = \varepsilon \varepsilon_0 \left( \frac{V}{z} \right)^2 A_{xz}. \]  

(2.15)

This actuation force is also known as the isometric force or blocked force [Meijer et al., 2001]. Since the actuation force \((dF)\) is proportional to the cross-sectional area \((A_{xz})\), strong actuators can be made by combining multiple layers of active film. Since the area \(A_{xz}\) changes with strain \((s_y)\), the above expression can be rewritten as

\[ dF = \varepsilon \varepsilon_0 V^2 \frac{x_0}{z_0} (s_y + 1). \]  

(2.16)

where \(x_0\) and \(z_0\) are the dimensions of the undeformed film. The reaction force of the actuator can be obtained by combining the elastic force (Equation 2.13) with the actuation force (Equation 2.16) [Kornbluh et al., 2001; Kofod, 2001]:

\[ F = k \left( y_0 s_y \right) - dF = k \left( y_0 s_y \right) - \varepsilon \varepsilon_0 V^2 \frac{x_0}{z_0} (s_y + 1). \]  

(2.17)

For small strains \((s_y)\), the actuation force predicted in Equation 2.16 can be considered constant. In the spring model, actuation can be viewed as displacing the spring equilibrium point by the addition of a weight \((dF)\), as shown in Figure 2.8b. The separation of the spring equilibrium points is the actuator stroke \(dy\), which is given by

\[ dy = \frac{dF}{k} = \frac{py_0}{Y}. \]  

(2.18)

For a given electric field \((E)\), the actuator stroke is independent of the material thickness. However, large strokes can be achieved by using an elastomer with a low modulus. The low modulus in turn implies that the actuator is inherently compliant.

2.3.2 Force-Displacement Curves and Work Cycles

Force and displacement are two key performance criteria of any actuator. Figure 2.9 shows the test setup that was used to generate the force-displacement curves of actuator prototypes. The actuator length \((y)\), which is the independent variable, is controlled manually and recorded with a linear variable differential transformer (LVDT). To avoid buckling of the film, the parallel beam actuator has to be under tension, meaning that the force reading of the load cell is always positive. The force exerted by the actuator is the dependant variable and is measured with a load cell. The data was
recorded with an oscilloscope and exported to Matlab®, which was used to perform analysis and generate graphs.

If the actuator behaved as predicted by the spring model, then the force-displacement curves shown in Figure 2.10 would result. The upper curve represents the actuator in its un-actuated state and is a graphical representation of Equation 2.12. Its slope is equal to the spring constant \( k \). Applying a voltage while the length is constrained reduces the tension in the actuator by the isometric force \( dF \). The lower curve on the plot represents the force-displacement in its actuated state. For small strains, the two curves can be considered parallel and separated by the amount of the isometric force \( dF \).

The loading conditions that maximize the work output are represented by the work cycle and indicated by the shaded region in Figure 2.10. The work cycle is generated by constraining the displacement of the unloaded un-charged actuator (state 1). A voltage is applied while holding the length constant, which is equivalent to adding the weight \( dF \) in the spring model (state 2). While keeping the electric field constant, the constraint is moved until the actuator force is zero (state 3). The voltage is then removed and the process is repeated. The area enclosed by a counter-clockwise work cycle corresponds to the work output per cycle. It is evident that the actuator force is not constant as it reaches its maximum force \( dF \) at the beginning and diminishes to zero.

This model assumes a quasi-static measurement. However, the viscoelastic properties of the polymer film cause the measured forces to be time dependent. A more sophisticated method that allows the determination of actuator power is the workloop.
technique, which is popular for characterizing biological muscles [Josephson, 1985; Meijer et al., 2001].

Although simple, the quasi-static spring model was found to be a very effective tool for actuator design and is sufficient to illustrate the actuator tuning that was performed to achieve effective binary operation.

![Diagram of linear quasi-static dielectric elastomer actuator model]

**Figure 2.10. Linear quasi-static dielectric elastomer actuator model**

### 2.3.3 Linear Actuators Prototypes

In comparison to the fixed frame actuator presented in Figure 2.2, for a simple linear actuator, expansion of the film is desirable to occur only in one planar direction. Constraining the film in the passive direction will cause the thickness compression to translate into expansion in the active direction. A constraint can be achieved mainly by pre-stretching the film in the passive direction. The non-linear elastic properties of the elastomer cause the film to stiffen with pre-straining, producing an output motion that is predominantly perpendicular to the high pre-strain direction. Figure 2.11 shows a fixed frame actuator expanding in only one planar direction. The maximum linear strain of about 240% was reached within 3 seconds. Reported values for the maximum area strains achieved by non-uniform pre-stretching are larger than with isotropic pre-stretching [Pelrine et al., 2000]. This is believed to be due to the fact that non-isotropic
pre-stretching increases the dielectric strength without increasing the material stiffness in the output direction.

![Figure 2.11. Fixed frame actuator with motion in only one planar direction](image)

Figure 2.11 shows an example of a linear actuator lifting a mass of a 150g by 6mm. The actuator film undergoes a linear strain of 40% and weighs less than 0.1g. The high force to weight ratio shows promise; however, there are some limitations associated with such an implementation.

The vertical sides of the film are free, allowing the film to bow in. From Figure 2.12b it is evident that the amount of pre-stretching in the passive direction is not uniform throughout the actuator film. Since the film is largely incompressible, it is thin close to the beams and thicker at the center. Applying an electric potential across the electrodes creates a non-uniform pressure and deformation of the film. Thus, not all areas of the film are actuated fully. Since the film is not constrained in the passive direction, it exhibits some motion in that direction upon actuation. This motion does not produce useful mechanical work. The challenge is to maintain the pre-stretched boundary conditions on the film without interfering with the desired motion of the actuator. One way to ensure uniformity in the film would be to increase the aspect ratio of the actuator. However, an extremely short and wide actuator would be inappropriate for many applications.

Another limitation of this type of actuator is that it can only work under tension, as the film would immediately buckle under compressive loading. These limitations can be addressed by integrating the actuator into a flexible frame.
2.4 Flexible Frame Actuator

The main purpose of the flexible frame is to maintain the boundary conditions on the film and provide a restoring force in the active direction.

2.4.1 Design

Since the actuator motion is intended to be linear, two parallel beams are used as the starting point for the frames. These beams are connected with a linkage that does not collapse under the tension of the film and does not interfere with the intended motion of the actuator. The geometry was chosen such that all areas of film undergo approximately equal expansion under actuation. This is necessary to ensure that the thickness remains uniform for the range of motion. Figure 2.13a shows a monolithic frame that was machined from a single piece of Delrin®. Flexibility is achieved by reducing the wall width of the frame border in the areas that function as hinges.

Figure 2.13b shows an exploded view of the actuator module with the stretched dielectric film integrated into its flexible frame. Higher actuation forces can be achieved by increasing the number of layers of film sandwiched between the frames. When using an even number of dielectric films, the electrodes can be arranged so that the two outer electrodes are both grounded. The high voltage is only present in the inside of the actuator and is thus shielded from the environment. The actuator module that was developed for the BRAID uses two layers of the dielectric polymer film.
Figure 2.14 shows a photograph of a flexible frame module before and after actuation. VHB® 4910 was used for the polymer film and silver grease for the electrodes. The electrical connections to the electrodes were made with small strips of adhesive copper tape.

A welcome side effect of the frame is that it significantly increases actuator shelf life. A common failure mode of the parallel beam actuator is tearing of the elastomer film. Due to the high strain of the material it is very sensitive to imperfections. Small cracks along the edges have a tendency to grow and eventually to propagate through the entire film, destroying the actuator. The frames counter this failure mode, as they provide a rigid border and inhibit the propagation of cracks. For the parallel beam actuator shown Figure 2.12b, the electrodes do not extend all the way to the edge of the film. This is to prevent arching around the edges of the film, which is a result of electric
charge traveling through the air from one electrode to the other. The flexible frame has shown to eliminate this risk. The frame does, however, reduce the range of motion by adding additional stiffness to the module.

2.4.2 Performance

Figure 2.15 shows the measured force-displacement curves the actuator module at 0kV, 5.5kV, and completing a work cycle. The stiffness curves are recorded by stretching the actuator and returning it to the original state. Some hysteresis is evident, which is attributed to the viscoelastic losses of the film and frame. To approximate the quasi-static behavior, the displacement was varied at a relatively slow rate during the measurement. The data for each of the three measurements was recorded over a period of 20 seconds. Both the flexible frame and the acrylic polymer contribute to the stiffness of the module, which is approximately constant over the range shown. This suggests that the Hookean model is sufficient in describing the quasi-static elastic behavior of the module. The isometric force ($dF$) is 2N, the stroke ($dy$) is 4mm, and the actuator stiffness ($k$) is 0.5N/mm.

![actuator force-displacement](image)

Figure 2.15. Force-displacement characteristics of flexible frame actuator
Kinematically, the actuator can be represented as a six-bar mechanism as shown in Figure 2.16. Since the module in its assembled state has a relatively high aspect ratio, the width remains almost constant throughout actuation. All regions of the active film undergo equal strain ($s_y$) in the y-direction. Neglecting forces in the passive direction, the module can be represented as a parallel beam actuator with a width ($x_0$) of 74mm.

![Figure 2.16. Flexible frame represented as a 6-bar mechanism](image)

Based on Equation 2.17, the force-displacement curves of the actuator at 0kV at 5.5kV can be predicted. The spring constant ($k$) was set to 0.5N/mm based on the measurement. Figure 2.17 shows a comparison of the predicted stiffness curves to the experimental work cycle.

The vertical separation of the two theoretical curves, which is equivalent to the isometric force, increases with actuator length. The measured isometric force is less than predicted. A possible explanation is that the film starts to buckle under the applied voltage, as is visible in Figure 2.14. The experimental stiffness curves for 0kV and 5.5kV are approximately parallel, which is predicted by the spring model in Figure 2.8b.

The spring model is now used to examine how changes of the parameters increase performance. Equation 2.18 predicts that the stroke is inversely proportional to stiffness. A low stiffness would therefore be desirable and can be achieved by combining the actuator with appropriate elastic elements that compensate for the inherent elastomer stiffness.
2.5 Linear Bi-Stable Elements (LBE)

The stiffness of two springs acting in parallel can be represented by a single spring with the spring constant being the sum of the two individual spring constants, i.e. \( k_e = k_1 + k_2 \). According to the spring model, an infinite stroke can theoretically be achieved if the stiffness is zero [Pelrine et al., 2000]. The goal is therefore to design a passive element with a negative stiffness to cancel that of the module. A bi-stable element is one such element that exhibits a negative stiffness for part of its range of motion.

2.5.1 Design

The LBE consists of a base that elastically supports two opposing flexure arms, as shown in Figure 2.18a. As a slightly oversized insert is placed between the arms, it preloads the base and causes the assembly to have two stable configurations, as shown in Figure 2.18b. Like the actuator, the LBE base and inserts were machined from a single piece of Delrin®.
The measurement setup introduced in section 2.3.2 can be used to measure the force-displacement profile of the LBE. A curve for a sample LBE is shown in Figure 2.19. The two stable equilibrium points are where the curve intersects the neutral axis with a positive slope. In between these equilibrium points, there is a region where the slope is negative and approximately linear. This linear negative region is of interest in compensating the actuator module.

Figure 2.18. Linear bi-stable element

Figure 2.19. LBE model and comparison to measurement
The force-displacement behavior of the LBE is a function of the geometry and material. To more effectively design an appropriate LBE, a mechanical lumped parameter model consisting of a link and a spring-loaded slider was generated, as shown in Figure 2.20. Since the LBE is symmetric about its vertical axis, the model only represents one half of the LBE. Expressing the vertical force acting on the insert as a function of displacement $y$ results in

$$F_{LBE} = k_b \left( 1 - \frac{L + \Delta x}{\sqrt{L^2 + y^2}} \right) y$$  \hspace{1cm} (2.19)$$

where $k_b$ is the spring stiffness and $L$ the length of the link. $\Delta x$ is the distance by which the spring is preloaded when the link is horizontal. It is equivalent to one half of the dimension by which the insert is oversized.

![LBE lumped parameter model](image)

*Figure 2.20. LBE lumped parameter model*

Figure 2.19 compares the force-displacement curve of the theoretical model with that of a measurement. The plots show good agreement with each other. The individual parameters of this model, especially the spring constant, are somewhat difficult to predict based only on the part geometry and material properties. It was therefore not used to calculate the exact curve. However, an understanding of the model is useful in predicting the effects of design modifications.

Figure 2.21 shows a CAD drawing with the dimensions labeled that are most critical to the slope and range of the linear region. By varying the width of the insert ($W_3$), the interference between the insert and base ($d_w = W_3 - W_1 = 2 \Delta x$) and thus slope of
the force-displacement curve can be tuned precisely. An increase in width of the insert corresponds to an increase in range and slope of the near linear region. As the insert and thus the load become too large, the flexure arms are prone to buckling. This suggests that the LBE of this configuration needs a sufficiently large width \((W_I)\) to achieve a given range of motion. The elastic behavior of the LBE is mainly provided by bending of the lower beam. Increasing the height \((H_I)\) or reducing the width \((W_I)\) of the beam is equivalent to increasing the spring constant \(k_b\) in the lumped parameter model.

The flexure arms form four-bar linkages and prevent the insert from undergoing rotational motion. The functional requirements of the arms are to be flexible and be able to withstand the compressive loads. The insert is mated with the base by using an interfering dove-tail.

![Figure 2.21. Drawing of LBE components](image)

### 2.5.2 Performance

The final LBE design was arrived at after performing a number of design iterations, each time measuring and evaluating the force-displacement profile. This was done by recording the range and slope of the linear region. A given base was typically measured with a number of inserts of different widths. It was attempted to minimize overall size and mass while maintaining functionality. The final size was similar to that of the flexible frame to maintain the overall dimensions of the module.

Figure 2.22 shows the force-displacement curves of LBEs with three different inserts. The actual measurement exhibits some hysteresis which is attributed to the
viscoelastic properties of the material. Table 1 lists the approximate slope and linear range for each measurement. To compensate the double layered actuator module above, an LBE is chosen that has a stiffness of -0.5N/mm over a large range.

![Linear Bistable Element](image)

**Figure 2.22. LBE force-displacement profiles for increasing size of the insert**

<table>
<thead>
<tr>
<th>Oversize of insert</th>
<th>Linear range (mm)</th>
<th>Stiffness in linear range (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>6.2</td>
<td>-0.44</td>
</tr>
<tr>
<td>4.0</td>
<td>8.4</td>
<td>-0.54</td>
</tr>
<tr>
<td>4.5</td>
<td>9.1</td>
<td>-0.70</td>
</tr>
</tbody>
</table>

*Table 1. LBE stiffness and range for various inserts*

### 2.6 Module Performance

#### 2.6.1 Compensated Actuator - Theoretical

Combining the actuator and the LBE is equivalent to summing the forces on the force displacement diagram. Figure 2.27a and b shows the diagrams without and with the LBE compensation, respectively.
For the compensated actuator case, the on and off curves have an identical shape, but are offset by the amount of the isometric force \((dF)\). A region is evident where the curves have a slope of approximately zero, which is equivalent in displacement to the linear region of the LBE. Beyond this region the slope increases rapidly, as the LBE has a positive slope in this area. The separation of the intersection point of the neutral axis is the actuator stroke \((dy)\), which has increased compared to the uncompensated actuator. For this force compensation method, the range of the LBE is the dominating determinant of the stroke, rather than the isometric force.

Relative position of the LBE to the actuator controls the location of the zero-stiffness region on the force-displacement diagram. For the case shown Figure 2.27, the LBE was positioned so that the center of the curve coincided with the midpoint of the actuator stroke. This way, the compensated module has equal magnitude of force in tension and compression in its linear area. Shifting the LBE position to the right in Figure 2.27a would result in an actuator that can exert higher forces under tension than compression. The actuator operating region can be adjusted for various applications. However, the stroke \((dy)\) and isometric force \((dF)\) remain unchanged.

![Diagram](image)

**Figure 2.23. Effect of the LBE on the idea actuator model**

While the above discussion of the actuator compensation was based on a forces analysis, it can also be approached by the energy method. The work output of the actuator is at its highest at the beginning of the stroke and decays towards zero. The LBE
stores potential energy from the beginning of the stroke and returns it to the actuator at the end.

A simple but effective analogy is to compare the actuator compensation to an elevator counter-weight, which is totally passive, yet makes the system more effective. The counter weight is equivalent in function to the LBE, which provides “counter-stiffness.” It cancels the weight of the empty elevator cabin, and the motor needs to only overcome variances in loading. A compensated actuator no longer needs to provide work to overcome its own stiffness, making all of it available to perform useful work.

2.6.2 Compensated Actuator - Experimental

Figure 2.24 shows an exploded view and a photograph of the actuator module. A screw attaches the LBE insert to the frame. It allows for a quick adjustment of the relative displacement between the actuator and the LBE. The module was tuned to have equal forces in compression and tension.

![Figure 2.24. Compensated actuator module](image)

Table 2 list the masses of the individual components of the entire actuator module. The most striking observation is that the active film accounts for only about 2%
of the total mass. This suggests that the most of the weight savings could be achieved by optimizing the frame and LBE, rather than the actuator itself.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active film (elastomer&amp;electrode)</td>
<td>0.2</td>
</tr>
<tr>
<td>Silicone adhesive</td>
<td>0.8</td>
</tr>
<tr>
<td>Flexible frames</td>
<td>4.6</td>
</tr>
<tr>
<td>LBE base</td>
<td>2.5</td>
</tr>
<tr>
<td>LBE insert &amp; screw</td>
<td>1.0</td>
</tr>
<tr>
<td>Electrical connections</td>
<td>0.1</td>
</tr>
<tr>
<td>Total Actuator Module</td>
<td>9.2</td>
</tr>
</tbody>
</table>

*Table 2. Mass of actuator module*

Figure 2.25 shows the corresponding work cycle plot. The actuator stroke has increased from about 4mm to 8mm. The active area of the film undergoes a linear expansion of about 57%. The plots exhibit the same general behavior as predicted by the model and suggests a constant force range of about 5mm. Some hysteresis is evident by the fact that the curve does not exactly return to its original position.

![Force-displacement diagram of compensated actuator module.](image)
Figure 2.26 shows the module's displacement and current input versus time. Upon actuation most of the length change occurs within two seconds, after which however the actuator continues to creep. If the actuator stroke is limited to the constant force range, this problem is eliminated. The peak input current reaches 37μA and quickly decays toward 3μA at steady state. At an input voltage of 5.5kV, the electrical power required to keep the actuator in its expanded state is 16.5mW.

![Actuator displacement and current versus time](image)

**Figure 2.26. Actuator displacement and current versus time**

The actuator module developed so far can work under both tension and compression and provides a constant force over a certain range. This actuator can be controlled using traditional feedback, which could be provided by an attached sensor. The actuator itself could be used as a sensor since its capacitance changes with displacement. The capacitance in turn could be measured electrically by superimposing a low power high frequency signal onto the power line, and measuring the frequency response.
While this offers a potentially interesting solution to certain applications, the goal here is to simplify robotics by replacing feedback control by open-loop binary operation.

2.6.3 Binary Action

As the elastomer tends to have a low modulus, the actuators are inherently compliant, and any external disturbance force $F_d$ creates a change in displacement. The actuator endpoints are thus a function of loading, which does not provide good repeatability. Repeatable endpoints can be achieved by limiting the actuator motion with hard stops to a smaller range $(d_{yhs})$.

A graphical representation is shown in Figure 2.27a for the uncompensated actuator. The unloaded actuator pushes against the hard stops with a force $F_s$. At either endpoint, the actuator will behave perfectly rigidly for disturbances up to $\pm F_s$. Since it is also maximum load the actuator can displace while still reaching its endpoints it can be considered the actuator force. It and can be expressed as

$$F_s = \frac{1}{2}(dF - kdy_{hs})$$  \hspace{1cm} (2.20)

While the uncompensated actuator module is capable of higher forces than $F_s$ over most of its range, these cannot be exploited under constant load applications. There is a tradeoff between actuator force $(F_s)$ and stroke $(d_{yhs})$. The maximum work that can be generated by a constant-load work cycle is achieved when $d_{yhs}=\frac{1}{2}dy$ and given by $U=F_s \times d_{yhs}$. Figure 2.27b shows a graphical representation of the effects of the hard stops applied to the compensated actuator, placed at the limits of the constant force range. The actuator force $(F_s)$ has increased over the uncompensated case, with the theoretical maximum actuation force being $\frac{1}{2}dF$, seen by setting $k=0$ in Equation 2.20. It is evident that the work generated by a constant load work cycle is close to the maximum capability of the actuator module.
This actuator makes effective use of the dielectric elastomer capabilities and provides robust binary operation for integration into the BRAID.

This module has some similar characteristics as a pneumatic actuator, which due to the compressibility of air is inherently compliant. By driving the piston to one extreme end, the pneumatic actuator behaves rigidly. To compress an extended actuator, the external load needs to exceed the force exerted by the compressed air on the piston.

### 2.6.4 Possible Improvements

The polymers used for the actuator exhibit viscous behavior. In the assembled state, the film, frame, and LBE are under stress and deform plastically over time. Since the compensated actuator module relies on a balance of forces, the performance decreases as the actuator ages. For a binary module, the endpoints are still maintained but the actuator force decreases with age of the module. The decay in performance has not been quantified. However, it seems that aging through stress relaxation rather than fatigue limits the life of the modules. It has been observed that the acrylic-based actuator modules tend to last only a few weeks. A silicone-based parallel beam actuators has maintained its performance for more than a year. Extensive fatigue testing has been performed at SRI. Tube-shaped silicon and acrylic actuators have been reported to maintain their performance over 10 million cycles [Kornbluh et al., 2002].

Searching for appropriate materials with better creep and stress relaxation properties could be a possible solution to improving the shelf and fatigue life of the
actuator modules. Also, designing the frame to have distributed compliance might help to reduce the effect of creep. With the current design, the flexures, which consist of a relatively small amount of material, allow the frame to deform and store the elastic energy. This causes high stresses in the flexures. The rate of creep increases with higher stresses, which can be reduced by distributing the elastic energy over a larger amount of material. [Kota, 1999; Askeland, 1994]. Figure 2.28 shows a flexible frame where links and flexures have been replaced by a single flexure. This design has not yet been evaluated in practice.

Figure 2.28. Flexible frame with distributed compliance
Chapter 3

Binary Manipulator Design

This chapter presents development of a dielectric elastomer-actuated binary manipulator. The third generation BRAID (BRAID III) design is based on the actuator modules, which function as structural elements with embedded actuation. The workspace of the BRAID III based on current and projected actuator performance is predicted. The development of a prototype demonstrates feasibility and illustrates some of the practical issues of using dielectric polymer actuators. A fourth generation manipulator design (BRAID IV) is also discussed. The actuators are embedded into the actual structure, rather than being in the form of modules.

3.1 BRAID III

3.1.1 Kinematics

A single stage of the BRAID is a 3 degree of freedom parallel manipulator. Kinematically the stage can be described by the joints connecting its linkages. Figure 3.1a shows a revolute-revolute-spherical (RRS) configuration, which was used in the earlier stage of the NIAC study for the first two BRAID generations and for the simulations [Lichter, 2001]. The BRAID III configuration is shown Figure 3.1b. The only difference is that the two links and its enclosed joint have been replaced by the actuator module, which behaves as a linear actuator. Since each actuator is controlled in a binary fashion, each platform can achieve $2^3=8$ discrete states.
3.1.2 Workspace

Unlike a continuous manipulator, the workspace of a binary actuator consists of a number of discrete points in space. It is an effective tool to describe the kinematic performance of a manipulator. The density of the workspace in a certain region corresponds to the precision of the actuator, which generally is not uniform throughout the workspace.

The workspace is a function of the BRAID geometry and actuator stroke. To illustrate the potential of the BRAID III design, a 4 stage (12DOF) manipulator is considered which has \(2^{12} = 4096\) discrete states. By assuming an overall length of the actuator module expanding from 28mm to 38mm, a realistic performance can be predicted and is shown in Figure 3.2a. With the lowest stage horizontal, the actuator module presented in Chapter 2 has enough force to support the manipulator in all states. The workspace size is on the order of a single stage of the BRAID. The high density would make such a design suitable for a micro-positioning device where high resolution is required rather than a large workspace.

The actuator modules are still in their early stages of development. The very high strains the dielectric elastomer can achieve under ideal conditions suggest that the dominant limitation to system performance is not the actuator material itself.
Optimization studies currently being performed on the frame and passive elements suggest that actuator strokes that are double those cited in Section 2.6.2 will be demonstrated shortly. Figure 3.2b shows the significantly larger workspace, using an actuator that expands from 28 to 48mm. The workspace diameter would then be on the order of the stowed BRAID III height. Such systems would lend itself to a variety of applications, such as a camera placement device for planetary exploration, see Figure 1.1.

The workspace clouds were generated by an algorithm that was developed by Matt Lichter as part of the NIAC study.

![Workspace clouds](image)

Figure 3.2. BRAID III workspace clouds (Mat. Lichter, 2002)

3.1.3 Prototype

The design goal of the BRAID III is to produce a virtually all-plastic, lightweight, binary manipulator. The kinematics shown in Figure 3.1 require a revolute joint to connect the module to the lower platform, and a spherical joint to connect to the upper platform. Figure 3.3 shows a skeleton of a single BRAID stage with the dielectric elastomer and LBEs removed.

Flexible hinges are wear free and their motions are smooth and continuous. They do not require any lubrication and are easy to machine. The revolute joint was realized by using a cross-flexural hinge, consisting of two plastic leaf springs. These springs are
crossed to provide good out-of-plane stiffness. The leafs were sized to have a good fatigue life and to provide low rotational stiffness [Hafez et al., 2002]. The spherical joint design is somewhat more complicated since it requires 3 degrees of freedom. However, the required rotation about the y-axis of the joint, as defined in Figure 3.3, is small. The hinge consists of a compliant plastic leaf connecting two pointed stiff elements, and approximates a spherical joint for small motions. Flexure hinge design was not the primary focus of this research, but easy to manufacture and lightweight solutions were found that met the functional requirements of the BRAID.

![Figure 3.3. BRAID skeleton without actuators showing flexure design](image)

The final design consists mostly of 2-D parts that were cut from Delrin® on a waterjet cutter. Grooves and holes in the individual pieces allowed them to be joined quickly and accurately, much like Legos™. The pieces are permanently held place with a small amount of glue.

All platforms are identical, and the upper platform of a given stage forms the base of the stage above it. This required each stage to be offset by 60° and resulted in a very compact design.
The platforms have a hole cut out of them in the center to allow of the routing of the power leads. The positive and negative electrical connections to the actuator were made by soldering wire wrap onto the two strips of copper tape attached to each actuator. The negative leads are all connected to a common ground.

Since the manipulator is intended to be binary, each DOF is controlled with a simple on/off switch, which is connected to the positive lead. A special high voltage switch was built to control the BRAID. While high-voltage switches are available commercially, they are generally rated for very high power application and are thus inappropriately large for controlling the BRAID.

A more elegant, but more expensive solution would have been to use a separate high voltage converter for each actuator. That way, the switching can be done with conventional low voltage components. This would also allow the control of the actuator directly from a computer, which could solve the inverse kinematics and planning for a high-degree of freedom BRAID. There would be no need for a digital to analog converter and no reason to worry about its related noise issues.
While some effort was made to keep the weight low, no systematic weight optimization was performed. Table 3 summarizes the mass contributions of the individual components towards a single stage of the BRAID III.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Actuator Modules</td>
<td>27.6</td>
</tr>
<tr>
<td>3 Lower hinges</td>
<td>3.0</td>
</tr>
<tr>
<td>3 Upper hinge</td>
<td>2.4</td>
</tr>
<tr>
<td>Platform</td>
<td>3.1</td>
</tr>
<tr>
<td>Wiring</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>36.4</strong></td>
</tr>
<tr>
<td>Weight of active film</td>
<td>0.6g</td>
</tr>
</tbody>
</table>

Table 3. Mass of BRAID III stage components

3.1.4 Performance

The actuator modules were powerful enough for the prototype to reach all of its states. It took about 3 seconds for a given actuator to change states. Figure 3.5 shows the prototype manipulating a hexagon mirror. An array of such binary manipulators might be a simple solution to focusing a large segmented mirror in space.

![Photograph of a 2-stage BRAID prototype.](image)

Comparing the BRAID prototypes gives good insight on the performance and potential of the dielectric polymer actuator technology. Figure 1.3 shows the prototype of the BRAID II, which had been developed earlier during the NIAC study. It has roughly the same dimensions as the BRAID III and uses electromagnets for actuation.
The voice coil and the dielectric elastomer actuators were developed to perform the same task. This serves as a basis of comparison of the two actuator technologies.

The function of the entire actuator module including the LBE is equivalent to the electromagnetic actuator leg shown in Figure 3.6.

![Figure 3.6. Single DOF of the electro-magnetically actuated BRAID II prototype](image)

A work cycle measurement of the entire leg was recorded using the similar method outlined in Section 2.3.2. Instead of switching the voltage off, the polarity is reversed, since the voice coil can provide force in both directions. To be consistent with the polymer actuator module, the isometric force \( (dF) \) is therefore twice the force the voice coil can achieve in a given direction. The force generated by the voice coil is proportional to the applied current. The maximum current was set to be as high as possible without overheating the actuator under continuous operation.

The two actuators are compared in Table 4. Since neither actuator could perform without the support structure, a comparison is most meaningful when the performance of the entire module or leg is considered. Due to its low density, the polymer actuator has about three times the work output on a mass basis than its electromagnetic counterpart. If only the mass of the active actuator, i.e. the coils and magnets or film and electrodes is considered, the true potential of the dielectric elastomers becomes evident. In this case, the work cycle per mass is about 70 times that of the electromagnets. The extent to which this high work density can be taken advantage of highly depends on how well dielectric elastomer actuators can be integrated into a structure.
<table>
<thead>
<tr>
<th>Actuation type</th>
<th>BRAID II</th>
<th>BRAID III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Isometric force (N)</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Work per cycle (mJ)</td>
<td>16</td>
<td>15</td>
</tr>
<tr>
<td>Mass of actuator &amp; structure (g)</td>
<td>20.0</td>
<td>9.2</td>
</tr>
<tr>
<td>Work per cycle per mass (J/kg)</td>
<td>0.5</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Comparison based on active components only

| Mass of active actuator (g) | 14              | 0.2               |
| Work per cycle per mass (J/kg) | 1.1         | 75                |

Table 4. BRAID II and BRAID III actuator comparison

There are many other parameters not listed in Table 4 that are important to evaluating an actuator. Unlike previous BRAID prototypes, the highly viscoelastic properties of the modules quickly damped out any vibration, which for this application is desirable. The main area for improvement is the reliability of the modules. The performance of the actuators built so far quickly decay with age. However, this is due to the behavior of the materials used, and does not represent a fundamental problem of dielectric elastomer actuators.

### 3.2 BRAID IV

#### 3.2.1 Design

For the BRAID III, the dielectric elastomers were integrated into the manipulator as self-contained actuator modules. Much of the weight of the module is due to the passive elements, which lowers the overall work density of these actuators. A more effective solution would be to integrate the dielectric elastomer directly into a structure of a manipulator or device. A mainly conceptual study was performed that considered such an approach.

Figure 3.7a shows the kinematics of a double-octahedral variable geometry truss, which forms a stage of BRAID IV [Rhodes, Mikulas, 1985]. Figure 3.7b shows a prototype of the truss without actuators. (Due to its geometry of triangular faces, it has earned the nickname “stealth” BRAID.)
Kinematically, a single BRAID IV stage has a revolute-spherical-revolute (RSR) configuration. It has 14 faces, 8 of which have a fixed triangular geometry. The remaining 6 faces form 3 diamond shapes. The two adjoining triangles that compose the diamond shape are approximately coplanar.

![Diamond-shaped area](image)

*Figure 3.7. Double-Octahedral Variable Geometry Truss (DOVGT) (Matt Lichter)*

The DOVGT is actuated by varying the diagonal length of the diamonds. Since this changes the enclosed area it is well suited for dielectric elastomer actuators. Figure 3.8a shows two diamond shapes with identical side length (L), but different areas. For a given change of the enclosed angle $\alpha$, the area strains are most significant when $\alpha$ is small. Thus, for the dielectric elastomer actuator to work well, the diamond has to be relatively skewed. Figure 3.8b shows a diamond shaped flexible frame actuator. Best results are achieved if the film is primarily stretched in the passive x-direction. Upon actuation the length increases in the y-direction, and decreases is the x-direction. For a flexible frame diamond actuator, the motions in either direction could be used to perform mechanical work. An interesting observation is that the actuator contracts in the x-direction upon the application of a voltage, and in this sense behaves like a natural muscle. Assuming $\alpha$ is less than 90°, the relative motions in the x-direction are smaller, but will produce a larger force than in the y-direction.
For the DOVGT, rather than using a separate frame the actuator would be directly attached to the structure. The dielectric film could be bonded to the sides of the structure, see Figure 3.7b. The elastic restoring force could be provided by the elastic flexure hinges. The function of the LBE, which is to tune the restoring force, could be also integrated into the hinges. A shampoo bottle cap is an example where bi-stable behavior is integrated into a rotational joint.

Of course, such an integrated system would come at the cost of added complexity to the design process, as actuators and structure can no longer be tuned independently. The motions of the individual actuator are no longer independent. Also, the assembly process would be challenging as the inside of the DOVGT and the inner electrodes would be difficult to access. However, none of these complexities pose a fundamental technical problem.

### 3.2.2 Projected Performance

Like in section 3.1.1, the workspace cloud was computed for a four-stage 12 DOF BRAID. Figure 3.9a shows the cloud that is based on current actuator performance, which assumed the diamond undergoes a linear strain of 36% in the y-direction. If this strain could be doubled, then a significantly larger workspace could be achieved, as shown in Figure 3.9b. Table 5 summarizes the values for the corresponding diamond dimensions for both scenarios.
Figure 3.9. BRAID IV workspace cloud (M. Lichter)

<table>
<thead>
<tr>
<th></th>
<th>Off</th>
<th>actuated</th>
</tr>
</thead>
<tbody>
<tr>
<td>based on current performance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>x (mm)</td>
<td>100</td>
<td>95.7</td>
</tr>
<tr>
<td>y (mm)</td>
<td>28</td>
<td>38</td>
</tr>
<tr>
<td>strain $s_y$</td>
<td></td>
<td>36%</td>
</tr>
<tr>
<td>based on predicted performance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>x (mm)</td>
<td>100</td>
<td>89.2</td>
</tr>
<tr>
<td>y (mm)</td>
<td>28</td>
<td>48</td>
</tr>
<tr>
<td>strain $s_y$</td>
<td></td>
<td>71%</td>
</tr>
</tbody>
</table>

Table 5. BRAID IV actuator geometries
Chapter 4

Conclusion

4.1 Summary of Results

This thesis presented the development of a polymer-based actuator module used to power a binary manipulator. The research focused on the effective implementation of dielectric elastomer actuators. This was achieved by integrating the actuator material into a flexible frame that maintains appropriate boundary conditions and provides an elastic restoring force. This actuator was tuned with a passive elastic element to achieve desired force-displacement properties. The corresponding physical model was developed and validated experimentally. The final actuator is a virtually all-plastic self-contained module that can work under both tension and compression and can produce a uniform force throughout its stroke. The actuator module can be integrated into a mechanical system much like a pneumatic actuator.

Actuator modules were used to power a six degree of freedom binary manipulator prototype. The module has better performance in terms of force and displacement on a weight basis than a voice coil actuator that was developed for the same application. Since the actuator module still exploits only a small fraction of the dielectric elastomer capability, optimization could lead to very high energy to weight ratios. Such performance has the potential of making high-degree of freedom binary robots practical.

4.2 Future Work

The actuator module concept presented in this thesis demonstrates good performance and warrants further research. Currently, the main limitation is reliability and short shelf life. This could be addressed by investigating alternative materials for the frames and by improving the quality of the assembly process. Optimization of the frame
and LBE geometries could lead to higher strains. A more efficient assembly process could also allow for a large number of layers of film and therefore high actuation forces. As long as the actuator performance in practical systems is significantly less than under laboratory conditions, continued work on actuator implementation is justified.

The BRAID manipulators studied in this research consisted of a serial combination of 3 DOF stages. Binary robots are not limited to such structures. An interesting field of research would be to study possible arrangements of a large number of binary actuators, such as in a large lattice structure. The individual actuators do not have to be identical. For example, a linear stage could consist of serial arrangement of binary actuators. The stroke of the actuator at the base would be the largest. The next actuator would have exactly half the stroke and so forth. This is analogous to digital computing, where a number is generally represented by bits of decreasing significance.

In the long term, the development of practical artificial muscle-actuated binary manipulators envisioned here will require efforts across multiple academic disciplines. Improved performance of dielectric elastomer actuators will require research of suitable polymer films, electrodes, fabrication methods, and electronic circuitry.

Material scientists will have to lead the way in the development of polymer films that are optimized for use as dielectric elastomers. To achieve large actuation pressures, an ideal film would have a high dielectric constant and a high dielectric strength. The development of thin films would reduce the required actuation voltage. Large strains are made possible by materials that can undergo large deformations and have a low elastic modulus. High efficiency is made possible by materials that have low viscous losses. The reliability and environmental tolerance of dielectric elastomer actuators is mainly dependent on the polymer film. Polymer materials can be found that have good properties for some the above parameters, but currently there is not a single material that exhibits good performance for all the criteria. For example, a polymer film with the electrical properties of VHB 4910 and the good fatigue and viscoelastic properties of silicone would make an excellent actuator. To date, no polymers have been specifically developed for use as dielectric elastomer actuators. Research would involve the synthesis of elastomer films which exhibit the desired key properties.
Current manufacturing techniques, while acceptable for laboratory
demonstrations, are too time consuming to be feasible for mass production. Research
could lead to fabrication method that produces multi-layered elastomer films and
electrodes in a single process. This research proposed flexible frames to provide pre-
stretching boundary conditions on the film. The film could be stretched by an array of
microscopic frames that are directly embedded into the film. Such dielectric elastomer
actuators could then be made available as an engineering material, possibly on a roll
much like adhesive tape.

4.3 Outlook

Dielectric polymer actuators have some unique properties. One of the most
interesting might be their geometry, as they can be made into extremely large thin sheets,
allowing them to be used in spaces where conventional actuators are too bulky. In such a
form, the dielectric elastomer can be viewed as a skin with actuation capability. This
could be used to control the shape of an airfoil. Such active skin could also be combined
with clothing to form a suit that provides motion assistance. The scale independence of
the dielectric elastomer operating principle makes small-scaled actuator feasible.

The NIAC study intends to explore concepts 10 to 40 year horizon, and many
topics suggested for future work could be addressed by then to make high-DOF binary
robots feasible. It is also believed that the actuator research presented here is more than
just distant concepts. Optimization of the described module could lead to powerful,
lightweight, and inexpensive alternatives to current actuator technologies.
References


References


Appendix A: HV Power Supply

The dielectric elastomer actuators require actuation voltage of several thousand volts. A special power supply was built to meet these requirements. A circuit schematic is shown in Figure A.4.1. The heart of the HV power supply is a commercial DC-DC converter (EMCO’s Q101-5) that has a fixed gain of 2000. Its maximum output voltage is rated at 10,000V and its maximum current is 50μA.

All switching and voltage regulation is done on the low-voltage part of the circuit. The power to the DC-DC converter is provided with a standard 9V battery through a variable voltage regulator. The input voltage can be externally controlled through a variable resistor (R6). The circuit was designed such that the high voltage output can be controlled over a range from 5 to 10kV. On the high voltage side of the circuit, a current limiting resistor (R3) protects the circuitry from incidental shorts. Since the high output voltage (VHV) of the power supply cannot be read with a standard multimeter the measurement has to be taken through a voltage divider. The voltage divider output is given by

\[ V_L = \frac{R_2}{R_1 + R_2} V_{HV} = \frac{100 \, k\Omega}{100 \, k\Omega + 1 \, G\Omega} V_{HV} = \frac{1}{10001} V_{HV} \]  

(A1)

The voltage divider resistors also function to drain the charge from the actuator after the supply has been switched off.
This circuitry and a 9V battery are housed in a compact plastic box shown in Figure A.4.2. The output voltage is regulated by varying the variable resistor with a screw driver through a small access hole. A removable cable connects the voltage divider to a standard multimeter.

![Image of circuit schematic]

**Figure A.4.1** Circuit schematic of power supply

**Figure A.4.2**. HV power supply: Output voltage can be set with a screw driver; removable cable allows for connection to a voltmeter.
Flexible frame:

all dimensions in mm
all rounds and fillets 1mm
part thickness 3.2mm; Material: Delrin (R)
Linear Bi-stable Element:

all dimensions in mm
part thickness 3.2mm; Material: Delrin (R)