Designing Components Using smartMOVE™ ELECTROACTIVE POLYMER Technology

Marcus Rosenthal, Chris Weaber, Ilya Polyakov, Al Zarrabi, Peter Gise
Artificial Muscle, Inc. 749 North Mary Ave., Sunnyvale, CA 94085
marcus.rosenthal@artificialmuscle.com

ABSTRACT
Designing components using SmartMOVE™ electroactive polymer technology requires an understanding of the basic operation principles and the necessary design tools for integration into actuator, sensor and energy generation applications. Artificial Muscle, Inc. is collaborating with OEMs to develop customized solutions for their applications using smartMOVE. SmartMOVE is an advanced and elegant way to obtain almost any kind of movement using dielectric elastomer electroactive polymers. Integration of this technology offers the unique capability to create highly precise and customized motion for devices and systems that require actuation. Applications of SmartMOVE include linear actuators for medical, consumer and industrial applications, such as pumps, valves, optical or haptic devices. This paper will present design guidelines for selecting a smartMOVE actuator design to match the stroke, force, power, size, speed, environmental and reliability requirements for a range of applications. Power supply and controller design and selection will also be introduced. An overview of some of the most versatile configuration options will be presented with performance comparisons. A case example will include the selection, optimization, and performance overview of a smartMOVE actuator for the cell phone camera auto-focus and proportional valve applications.

KEYWORDS
SmartMOVE, linear actuators, electroactive polymer, dielectric elastomer, Artificial Muscle, auto-focus actuator, proportional valve, bias mechanism

1. INTRODUCTION
SmartMOVE offers a unique capability for devices and systems of creating customized motion that is challenging to achieve with electromagnetic and other traditional actuators. Since the technology enables new design methodologies, clear and concise design guidelines are necessary to be prepared for engineers and designers to integrate this new actuator technology into their systems. Artificial Muscle, Inc. has developed techniques that will be outlined in this paper for characterizing smartMOVE actuators that enable industry and the electroactive polymer community to design actuator components. To begin designing components using smartMOVE actuators for a specific application, the designer must have as much information as possible of the operating specifications such as form factor, force-stroke profile, duty cycle, response time, environmental operating conditions, lifetime, and additional application specific requirements.

SmartMOVE is based on a dielectric elastomer type electroactive polymer that has been commonly referred to as Electroactive Polymer Artificial Muscle (EPAM). SmartMOVE EPAM consists of a thin layer of polymer film between two conductive, compliant electrodes. When a voltage potential is applied across the electrodes, the Maxwellian pressure causes the electrodes to attract each other, and since the film is elastomeric and incompressible, the film contracts in thickness and expands in area. The technology is essentially an elastomeric capacitor that is capable of changing capacitance by applying a voltage or by an external mechanical force. SmartMOVE can operate in generator mode by having external work operate on the system which changes the net charge on the capacitor and energy is generated. Similarly, smartMOVE can be used in sensor mode by measuring the capacitance to monitor the position or force on the component. There are many possible configurations for SmartMOVE electroactive polymer actuators such as extenders, unimorphs, diaphragms, framed, rolled, tubes and thickness mode.
2. smartMOVE OVERVIEW

The Universal Muscle Actuator™ (UMA™) diaphragm configuration of electroactive polymer technology has been chosen as the basis for the design examples in this paper because this configuration serves a wide range of customer applications for electroactive polymer technology and serves as a useful development platform for product design. The UMA is a standard, modular building block for linear actuators that can be implemented for a wide range of configurations in many applications with minimal customization. The Universal Muscle Actuator (UMA) shown in Fig. 1 consists of a planar ring of EPAM film held in a rigid frame that can be assembled into a final actuator.²

When a voltage is applied to the UMA cartridge, the planar ring of EPAM film expands as a result of the Maxwellian pressure acting on the elastomeric film. In order to get motion out of a UMA or any smartMOVE actuator, an external bias needs to act on the cartridge. This bias will provide a force to create a preferential direction of motion. Figure 2 shows the weight bias configuration, Figure 3 shows the compression spring bias configuration, and Figure 4 shows the film bias configuration. There are a variety of additional potential bias mechanisms such as air pressure, tension springs, leaf springs, foam, or a number of custom spring designs.

The force balance of the system at equilibrium is equal to 0 and is shown by equation

\[ F_{LOAD} + F_{ELEC} + F_{BIAS} + F_{FILM} = 0 \]  (1)

Where \( F_{LOAD} \) is the force of the external load, \( F_{ELEC} \) is the force due to the electrostatic pressure applied by actuation, \( F_{BIAS} \) is the force of the bias mechanism, and \( F_{FILM} \) is the elastic restoring force of the EPAM film. The position of the output disc or stroke of the devices is based on how the force balance of the system changes during actuation. The motion of the smartMOVE actuator is created by an increase in \( F_{ELEC} \) which reduces the \( F_{FILM} \) by increasing the length of the film and reducing the elastic tension in the film. Thus, the smartMOVE actuator can be modeled as a variable spring rate \((k)\) spring. Figure 5 shows the model as a single phase device and Figure 6 shows the model as a two phase device.
The Active Equilibrium position is then determined by the force-stroke profile of the $F_{LOAD}$ and the $F_{BIAS}$. Where the $F_{LOAD}$ is unique for each application and the $F_{BIAS}$ is given by the load profile of the bias mechanism. For a weight bias, the $F_{BIAS}$ remains constant, thus can be called constant force bias. For a linear spring bias, the $F_{BIAS}$ is determined by Hooke’s Law.

3. CARTRIDGE CHARACTERIZATION

Designing an actuator using smartMOVE technology begins with characterizing the variable stiffness profile of the UMA cartridge, then developing the force profile of the biasing mechanism to optimize the EPAM cartridge performance. Artificial Muscle, Inc. has developed methods for UMA Characterization and bias mechanism design for optimal smartMOVE performance.

As an example of how stroke can be optimized with the appropriate bias mechanism, Figure 7 shows voltage actuation of a 50 mm UMA cartridge with both a constant force bias (Weight Bias), and a UMA cartridge bias (Film Bias). By using a constant force bias, the actuator is able to achieve over 3X the actuation displacement at the same voltage. The constant force bias defines the upper limit of smartMOVE actuation using biasing mechanisms with spring rates $> 0$, such as other UMA cartridges and coil springs. This also shows that Biasing Mechanism Design plays a critical role in actuator design performance. Artificial Muscle’s method for UMA cartridge characterization involves measuring the passive and active cartridge stiffness and then calculating what the stroke would be at the constant force bias condition. Non-conventional biasing mechanisms which supply constant force as well as other load profiles will be discussed later in this paper.

To illustrate the stroke with a constant force bias mechanism, Figure 8 shows the weight bias of a UMA cartridge. The EPAM film stretches under the force of the weight, until it reaches a force equilibrium. This is the UMA’s Passive Equilibrium Position for the force applied. Upon the application of a voltage, the Maxwell pressure modifies the polymer strain and changes the equilibrium position to a second point, this is the UMA’s active equilibrium position for the force applied. Repeating this measurement for a range of weights (forces), gives you the UMA’s passive and stiffness curves as shown in Figure 9. The actuation displacement is simply the change in equilibrium position with applied voltage.

In the passive and active stiffness test, the bias force is controlled using a dynamic materials tester such as an Instron or Muscle Lever and the displacement due to the force is measured. The cartridge is characterized by starting at zero force...
and ramping up to the maximum desired force level. Any given diaphragm will have a maximum suggested displacement, so the proper size diaphragm must be selected in order to achieve the required stroke. As seen in Figure 9, the constant force bias line has been added to the graph. The intersection of the constant force bias line and the passive and active stiffness curves represent the UMA position at the passive and active equilibrium states or in other words the device stroke. The blocked force of the UMA is the difference in force on the vertical line that intersects the constant force bias line and the passive stiffness curve.

![Figure 8: Weight Bias with Equilibrium Points](image)

Characterizing the UMA’s performance and optimum can be visualized by a 3 dimensional plot showing constant force, voltage, and actuator output. For the example shown, the output is a DC actuation displacement. Figure 10, shows the 3D plot of these variables. The optimum constant bias force shown on the 3D plot was used to generate the constant force bias data in Figure 11. The optimum constant bias force is dependent on the voltage applied to the UMA cartridge. A comparison of the actuation voltage performance optimums can best be viewed in a 2D plot of actuation displacement versus constant bias force as seen in Figure 11.

![Figure 9: UMA Passive and Active Stiffness](image)
The actuation voltage for a particular dielectric elastomer and electrode combination is based upon, among other factors, the polymer chemistry, measured dielectric breakdown strength and the reliability and performance criteria for the actuator design. AMI has designed a number of economical power supplies to provide for high volume electroactive polymer actuator applications. Designing UMA materials and configurations to operate within the limits of these power supplies is a key competency of AMI and has been achieved with many different dielectric polymer chemistries. These engineering and design methodologies are not covered within the topics reviewed in this paper. Given that the voltage response and dielectric performance is understood within the UMA’s capabilities, the actuation displacement vs. constant bias force provides UMA and bias mechanism design criteria for optimal performance.

As stated previously, a constant force bias mechanism defines the upper limit of electroactive polymer actuation using conventional biasing mechanisms such as coil springs. But, in most real applications it is challenging to use a true constant force bias. So, often a positive rate bias, such as a compression or tension spring is used. Figure 12 displays how the stroke compares for positive rate, negative rate, and constant force bias mechanisms. This shows the advantage
of using constant force and negative rate bias mechanisms. Bias mechanism effects on the performance, time response, repeatability, and reliability of the UMA cartridge are all important considerations in actuator design.

Figure 12: Passive and Active Stiffness Curves with Various Bias Mechanisms

4. SPEED RESPONSE

The speed response of a smartMOVE actuator is determined by a number of factors such as the dynamic properties of the dielectric polymer material, the resonant frequency of the actuator system, and the power supply. The dynamic properties of the dielectric polymer material can be characterized by evaluating the material with Dynamic Mechanical Analysis (DMA). DMA is performed using a technique of oscillating the force on the material and measuring the displacement. The stiffness of the sample can be determined and the storage modulus, loss modulus, and tan δ can be calculated. The parameter that gives the best representation of speed response and damping is the tan δ. Tan δ is the loss modulus divided by the storage modulus where storage modulus is a measure of how much elastic energy is returned and the loss modulus represents how much elastic energy is lost. The speed response will also be determined by the resonant frequency of the actuator system. The actuator system includes a smartMOVE actuator, bias mechanism, and all associated mechanical parts necessary to couple to the system. The third design element that determines the speed response is the power supply. The response time of the power supply is determined by the type of voltage step-up, series resistance, and the overall power of the supply.

5. RELIABILITY AND ENVIRONMENTAL RESPONSE

Actuator reliability is an important metric for any application. The voltage specific performance will be a trade-off with reliability, so the actuator needs to be sized accordingly to make sure that there is sufficient design safety factor to meet the reliability required. A theoretical model of performance vs. reliability is challenging to develop, so Artificial Muscle, Inc. has focused on experimental validation of reliability. But, in order to properly qualify the reliability for a given application, the smartMOVE actuators must be subject to the same loading conditions, duty cycles, and environmental conditions as the specific application. The most common failure mechanisms are dielectric breakdown and mechanical failure. Dielectric breakdown can be caused by operating at electric fields too close to the dielectric breakdown strength.
of the material and mechanical damage to the EPAM film that can damage the dielectric. Mechanical damage of the film can be caused by improper cartridge installation and handling procedures.

smartMOVE Actuators have a temperature and humidity response that is determined by the dielectric material properties. For example, acrylic elastomers and adhesives such as 3M VHB Tape have a temperature response that peaks near 25°C and drops off significantly below zero and silicone elastomers have a relatively flat response across temperature as can be seen in Figure 13. High humidity has been demonstrated to increase the dielectric leakage current. Leakage current has been demonstrated to be an indicator of the quality and reliability of a dielectric film. If an actuator is likely to be subject to high humidity, then a low moisture absorption dielectric material must be selected in order to achieve high reliability.

![Figure 13: Example Temperature Response of smartMOVE Actuators Based on Acrylic and Silicone Dielectric Materials](image)

6. ALTERNATIVE BIAS MECHANISMS

As described in Section 3, Bias Mechanism design plays a critical role in actuator performance. UMA cartridge design and bias mechanism design equally determine the actuator’s mechanical performance and must be integrated to provide optimal performance. The choice of bias mechanism is best determined by the application requirements. Constant force mechanisms allow greater actuation performance than a coil spring or cartridge bias. The best example of this mechanism is a weight. Weights offer limited use for most actuator designs but have been used for EPAM applications for Energy Generation. Compliant slider mechanisms have also been designed to supply constant output forces. Figure 14 shows an example of a constant force mechanism.

![Figure 14: Compliant Slider Constant Force Mechanism](image)
Bi-stable mechanisms have also been engineered to optimize UMA cartridge performance similarly to a negative rate mechanism. Load response matching between the cartridge and the UMA is achieved by matching the two bi-stable load points to the Passive and Active equilibrium points of the UMA Cartridge. Figure 15 shows an example of a bi-stable mechanism.

![Figure 15: Centrally Clamped Parallel Beam Bi-Stable Mechanism](image)

**7. ACTUATOR APPLICATIONS**

The actuator application will determine the operating region on the Load Response curve. Applications such as a haptic feedback, brakes or clutches require a small stroke but must deliver a high force. This operating region is shown in Fig. 15 along the vertical force axis. Low force, high stroke applications such as lens positioners for auto-focus systems will lie along the horizontal stroke axis where the requirement is for low force but large stroke. Combined output applications such as valves, pumps and actuators under load will need to operate at the mid-stroke/mid-force point in order to produce maximum useful work.

![Figure 16: Force vs. stroke operating profiles for various applications](image)

UMA actuators exhibit maximum available force at zero displacement (restrained) and zero force at the maximum displacement (unrestrained), as shown in Fig. 16. The actual operating point is determined by the additional design requirements such as frequency, lifetime and etc. The actual operational requirements for a particular application will define the optimum UMA diameter, number of EPAM layers per cartridge, and number of UMA cartridges required.
**8. DESIGN EXAMPLE: AUTO-FOCUS ACTUATOR FOR CELL PHONE CAMERA**

Application specific advantages offered by smartMOVE technology make it a natural choice for optics positioning applications. Positioning accuracy – the UMA force, i.e., position when biased is exactly proportional to input voltage, therefore, the positioning resolution is as good as the control electronics. 1-2um positioning steps have been achieved successfully by AMI. Damping and shock resistance – because smartMOVE film is a visco-elastic polymer, an overdamped system will result when used with most types of bias. This is advantageous in reducing or eliminating the “ring” present in current voice-coil positioning systems thus forming an easier to control system. SmartMOVE film is inherently shock resistant which makes it very attractive for mobile use.

![Mechanical Model of Auto-focus Application](image1)

**Figure 17: Mechanical Model of Auto-focus Application**

![Auto-focus Actuator Detail](image2)

**Figure 18: Auto-focus Actuator Detail**

A single phase UMA actuator forms the simplest embodiment of an optical positioning system. The system consists of a lens, or a set of lenses mounted in the center of the UMA cartridge, biased by a coil spring as seen in figure 18. In this configuration, the position of the lens will be a function of applied voltage as the system is always in equilibrium between the bias spring force and that of UMA cartridge voltage controlled spring ($F_e+F_b=0$). Selection of the UMA cartridge size and layer type/count depends on desired form factor, the mass of the lens assembly to be moved and the amount of movement required to span the focus range. For the sake of this example, lens mass will be neglected, leaving actuator stroke as the driving design factor. To a large extent, cartridge size required to achieve necessary travel will be the limitation of the form factor.

Given required stroke, one can undertake an iterative process to find the best cartridge size/bias spring combination using the passive/active cartridge stiffness data. As seen in Fig 12, an optimal operating zone exists for a given cartridge where the maximum amount of stroke per given voltage can be obtained. The goal of the designer is to pick a cartridge size and bias method with the lowest possible spring rate and allow all system equilibrium points to take place within the max stroke area of the curve and obtaining the linear displacement necessary for the application. In case of a coil spring bias, package form factor will drive the spring size but in all cases, a spring with the lowest rate which can fit the package is desirable.
9. DESIGN EXAMPLE: PROPORTIONAL VALVE

The UMA based actuator is very suitable for controlling the opening and closing of a fluid valve. SmartMOVE technology offers several advantages in controlling valves that make it a superior candidate for this application. Application specific advantages include power consumption - smartMOVE film is capacitive based and therefore does not draw significant power while maintaining active position - unlike solenoids. This eliminates heating and drastically reduces power consumption. Secondly, smartMOVE film has considerably higher power density than solenoids or piezo actuators which allows for much lighter valves. Lastly, the relationship of actuator mechanical output to input voltage is considerably more linear and more predictable than that of solenoids resulting in a simpler control system. There are of course numerous other non application-specific advantages offered by smartMOVE.

![Figure 19: Mechanical Model of Proportional Valve Application](image)

Figure 19: Mechanical Model of Proportional Valve Application

The poppet valve application is of particular interest as it requires both an application of a passive preload (poppet sealing force) and some active stroke after the preload is removed to allow fluid flow. In its simplest form, the valve is comprised of a UMA single phase actuator connected to a poppet which is forced to cover an orifice as shown in Figure 20. The single phase actuator is comprised of one or multiple UMA diaphragm cartridges and a bias spring.

![Figure 20: Mechanical Model of Proportional Valve Application](image)

Figure 20: Mechanical Model of Proportional Valve Application

The system can be found in 2 discrete states:

1. Flow is blocked - the UMA cartridge is passive and overpowers the bias spring to exert a sealing force \( F_b + F_p \) \(- F_e = \text{non 0} \) on the poppet.
2. Flow is restricted but moving – the UMA is active where the UMA output force is proportional to applied voltage \( F_e = xK_e[V] \). The system is in equilibrium which can only be altered by changing inlet pressure, therefore changing \( F_p \), or voltage which would change \( F_e \). In this mode the flow is roughly proportional to the voltage applied – the proportionality is affected by the fluid dynamics of the orifice/poppet and the exponential voltage response of the UMA.

As with any application, thorough understanding of the operating parameters is essential for selecting the right actuator. Final valve form-factor is one of the main driving forces behind the selection of the UMA cartridge size. Electrical requirements or limitations allow for a definition of the maximum operating voltage which is combined with available
film breakdown limits to determine the film used in the actuator. Fluid dynamic requirements govern the orifice and poppet size, which in turn dictate the zero-flow sealing force and the poppet opening distance. Knowing the above narrows the number of design variables until one is left with the number of layers and the bias spring type.

At this point, through an iterative process, one can tune the load response curve to obtain the necessary opening stroke given a required preload force. Layers can be mechanically coupled in parallel to achieve higher sealing force or higher stroke.

### 10. CONCLUSIONS

SmartMOVE’s unique application of actuation technology has garnered much interest in the design and use of UMA cartridges and their integration into commercial applications such as Lens Positioners, Pumps, Valves and Tactile Feedback actuators. A test technique of characterizing the active and passive stiffness of the smartMOVE actuator and using those curves to select and design the proper bias mechanism has been presented. This design methodology can be
extended to any smartMOVE EPAM actuator configuration. The goal of this paper is to provide a design guide that can enable designers to understand how to integrate this novel and enabling features of smartMOVE actuators into their product designs. Artificial Muscle, Inc. is continually developing smartMOVE EPAM technology to address broader actuator, sensor and generator applications by developing materials for improved reliability, environmental tolerance, and performance; design techniques to provide guidelines for easy integration; and configuration development for new applications.

REFERENCES


