# OVERVIEW OF NASA LANGLEY'S PIEZOELECTRIC CERAMIC PACKAGING TECHNOLOGY AND APPLICATIONS

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**ABSTRACT**

Over the past decade, NASA Langley Research Center (LaRC) has developed several actuator packaging concepts designed to enhance the performance of commercial electroactive ceramics. NASA LaRC focused on properly designed actuator and sensor packaging for the following reasons, increased durability, protect the working material from the environment, allow for proper mechanical and electrical contact, afford "ready to use" mechanisms that are scalable, and develop fabrication methodology applicable to any active material of the same physical class. It is more cost effective to enhance or tailor the performance of existing systems, through innovative packaging, than to develop, test and manufacture new materials. This approach led to the development of several solid state actuators that include THUNDER, the Macrofiber Composite or (MFC) and the Radial Field Diaphragm or (RFD).

All these actuators are fabricated using standard materials and processes derived from earlier concepts. NASA's fabrication and packaging technology as yielded, piezoelectric actuators and sensors that are easy to implement, reliable, consistent in properties, and of lower cost to manufacture in quantity, than their predecessors (as evidenced by their continued commercial availability.) These piezoelectric actuators have helped foster new research and development in areas involving computational modeling, actuator specific refinements, and engineering system redesign which led to new applications for piezo-based devices that replace traditional systems currently in use.

Keywords: THUNDER, Macrofiber Composite, Radial Field Diaphragm.
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## 1. INTRODUCTION

Piezoelectric ceramic wafers are inherently brittle and difficult to use in applications where a physical connection is needed to convert electrical energy into mechanical work. Recognizing this, the vendors of these electroactive ceramics developed three major elements based on the single wafer, the unimorph, the bimorph and the stack. The unimorph is a wafer attached to a shim. The bimorph consists of two bonded wafers poled either in series or parallel. The stack consists of many electrically connected individual wafers bonded together.[1-3] These elements are used in the design of pumps, igniters, positioning stages, transformers and acoustic transducers.[1-3] A drawback to these piezoelectric elements is that for many applications, the user must provide additional means of protection and fixturing in order to mitigate device failure while maximizing operational efficiency. This is demonstrated by the amount of additional hardware modification required to make the "as purchased" piezo-element functional in the final product. NASA's research for aerospace hardware continues to focus on ways to make components lighter, smaller, more power efficient, less complex, and operationally cost effective. Piezoelectric systems were viewed as a technology that could meet those objectives. Unfortunately, the components that were commercially available in the late 1980s were not designed for these new applications, so research was started to alter the performance of these materials by creating platforms that allowed for the simplification of the engineering designs. NASA created several simple elements using conventional laminating processes to produce the THUNDER, MFC and RFD piezoelectric actuators. The THUNDER actuator is in part based on the RAINBOW piezoelectric developed at Clemson University, MFC is derived from the Active Fiber Composite "AFC" and RFD is an evolution of the MFC and THUNDER (Fig. 1).[4-8] The THUNDER wafer is an actuator that has increased motion along the Z-axis, and is infinitely tailorable through the selection of laminating components.[4] The basic MFC is an in-plane actuator that has an increased component of unidirectional strain.[5] The RFD is similar to the THUNDER device in that it displays exaggerated Z-axis displacement, but the electric field is radially distributed.[7,9]

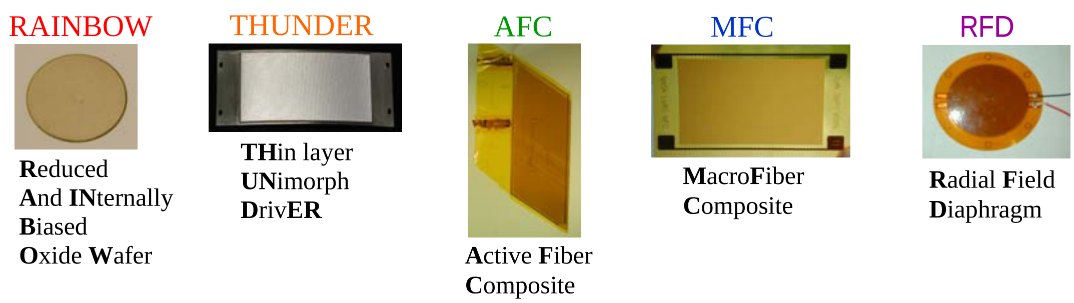


Figure 1. Examples of Single Wafer Actuator Technology - post 1990.

The NASA actuators are commercially available. Researchers worldwide have demonstrated the following uses for these technologies, piezoelectric motors, optical strain gauges, vibration suppression, airfoil shaping; structural vibration, health monitoring, acoustic transduction, computational modeling development, precision valve control and metering, synthetic jets and energy harvesting.

## 2. EXPERIMENTAL

### 2.1. THUNDER Fabrication

An electroded lead zirconate titanate (PZT) wafer is sandwiched between two layers of adhesive film surrounded by a thin metal shim on top and a thicker shim on the bottom. The layered structure is placed in a hot press or autoclave and pressure bonded according to the cure schedule of the adhesive. Wires are attached to the (+) top and (-) bottom metallic layers of the laminate. The device is DC poled according to the ceramic manufactures instructions (Fig 2).[4]

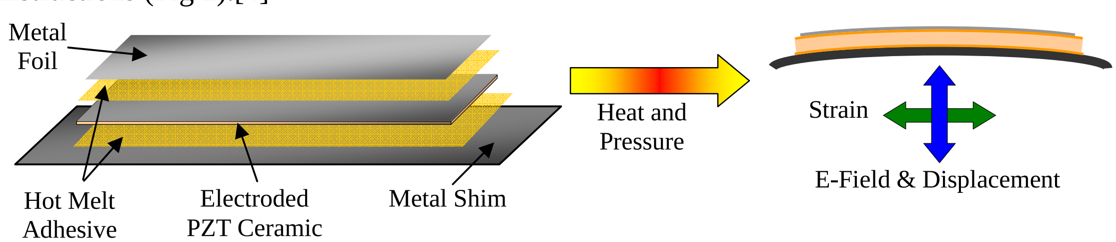


Figure 2. THUNDER Assembly Diagram with Cross Section.

### 2.2. Macrofiber Composite Fabrication

A bare PZT wafer is placed on a grip frame and parallel slices are cut with a dicing saw. Liquid dielectric adhesive is applied to the diced wafer, which is then inverted and placed against a pre-patterned copper clad polyimide film. The assembly is heat staged, resulting in the partially cured adhesive becoming tackier than the grip tape. The grip tape is peeled away, leaving the ceramic fibers lightly bonded to the bottom layer of copper clad polyimide. A second layer of liquid adhesive is applied and doctored flush against the fibers. A second adhesive coated pre-patterned copper clad film, copper side down, is placed against the coated fibers. The assembly is placed in a heated vacuum press and pressure bonded according to the adhesive cure schedule. The laminate is removed, wires are connected, and the MFC is DC poled per the ceramic manufacturer's instructions (Fig 3).[10]

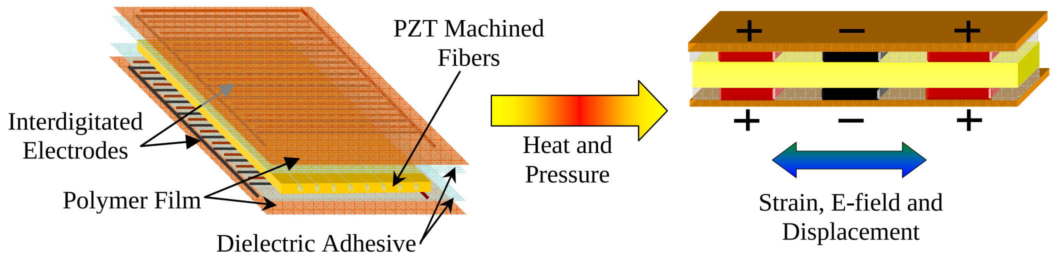


Figure 3. MFC Assembly Diagram with Cross Section.

### 2.3. Radial Field Diaphragm Fabrication

A bare PZT wafer is sandwiched between two mirror imaged copper patterns, coated flush with viscous adhesive, on polyimide film. The polyimide-copper faces are placed against the top and bottom surfaces of the ceramic wafer. The layered assembly is placed in a heated vacuum press and pressure bonded according to the adhesive cure schedule. The laminate is removed, wires are connected, and the RFD is DC poled per the ceramic manufacturer's instructions (Fig 4).[7]

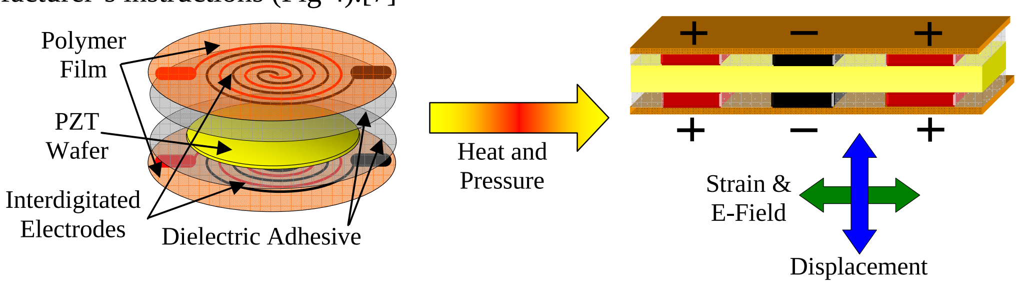


Figure 4. RFD Assembly Diagram with Cross Section.

## 3. RESULTS AND DISSCUSSION

### 3.1. Fabrication and Design Issues

All the NASA piezoceramic actuators are created using a laminate architecture and pressure bonding. Therefore, the most critical element is the adhesive which must exhibit the following characteristics: high shear strength in order to transfer force, proper melt flow or viscosity to insure a suitable bond, high dielectric strength to avoid arcing, and resistance to temperature and moisture to mitigate electrical shorts. Another critical factor is the protective packaging which must resist cyclic fatigue, maintain adequate compliance and impart impact resistance and durability with efficient load transfer. Lastly, the selection of the active material plays an important part in the performance of the resulting actuator.

The THUNDER actuator consists of four (4) materials bonded together; a heavy metallic bottom layer, a high temperature adhesive, the ceramic wafer, and the light metallic top protective layer. A mechanical pre-stress is imparted through a thermal mismatch created by the metallic bottom layer and the ceramic following elevated temperature bonding. The amount of pre-stress is related to the total force the bottom metallic layer can impart to the ceramic, and the temperature difference between the operational environment and where the adhesive bond imparts sufficient shear strength to transfer the internal mechanical strain. It is a d31 device that moves in the 3-direction. The THUNDER actuator derives its motion from the curved geometry, which can be varied based on the type and thickness of the metallic layer versus that of the piezoelectric wafer. This allows the performance of the device to be modified to fit the engineering application. The packaging provides attachment to the actuator, and the metallic layers, in combination with the adhesive add toughness and resistance to fatigue and crack propagation.[8]

The basic MFC is an in-plane actuator that has a high component of unidirectional force. It is a d11 device wherein the electric field and the strain are parallel and off axis strains are minimized by design. The RFD is similar to the THUNDER device in that it displays exaggerated Z-axis displacement, but is packaged like the MFC wherein the electric field is radially distributed. Thus, it could be termed a “dr1” device. Both the MFC and the RFD consist of three materials: the piezoceramic; the adhesive; and the polymer film. The adhesive must be in a liquid form, e.g. a two part epoxy, as it must flow between the narrow copper traces on the polymer film and, in the case of the MFC, between the diced ceramic fibers prior to thermal curing. The exterior packaging must be compliant and elastic enough to transfer the force of the ceramic while providing electrical insulation and a proper bonding surface.[11] The geometric design factors for MFC and RFD are the ceramic thickness and the electrode spacing that influence the electric field lines (Fig. 5).

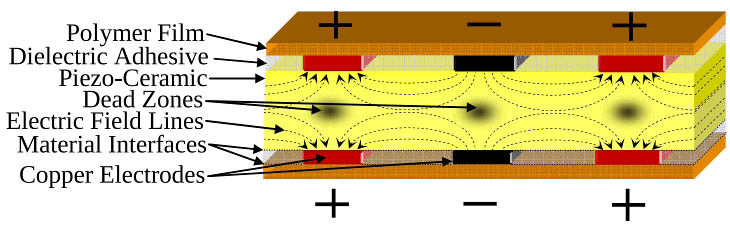


Figure 5. Cutaway Accounting for Design Factors for Performance Considerations.

In Fig 5, an effect is shown where “dead zones” occur based on electrode spacing and ceramic thickness. At high voltage potentials, current leakage along the material interfaces, can occur based on electrode spacing and material properties, because dielectrics have some degree of permittivity based on temperature, mechanical strain and contaminants. Thus, electro-mechanical efficiency of the MFC and RFD, like THUNDER, are based in part on geometric and operational factors. In all cases, shear is the dominant force transmitted from ceramic to the substrate via the packaging, and it is the adhesive bond that holds the device together and provides the desirable characteristics to the actuators.

**3.2. Performance**

The performance of the MFC is rather straight forward. The ceramic strains and displaces in the same longitudinal direction, with the transverse direction minimized by the influence of the non-active dielectric adhesive between the fibers. As shown in Fig. 6, by halving the center-to-center (C-C) electrode spacing, MFC1 vs. MFC2, almost doubles the longitudinal strain approaching that of the pure ceramic, d31 device. What is important is the total amount of in-plane strain obtained from the MFC as a result of its packaging.[12]

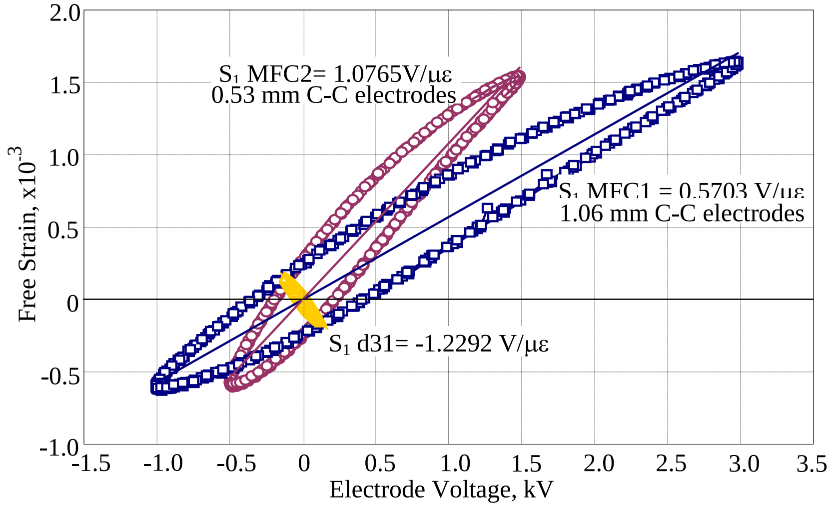


Figure 6. Slopes "$S_1$" of Strain vs. Voltage for MFCs and Standard Wafer, all 175 μm thick PZT-5A Type at 1 Hz Sine.

The actuators that displace out of plane, THUNDER and RFD, as a function of their in-plane strain are shown in Figs 7 and 8 where XY-strain gauges are attached to the actuator surfaces.

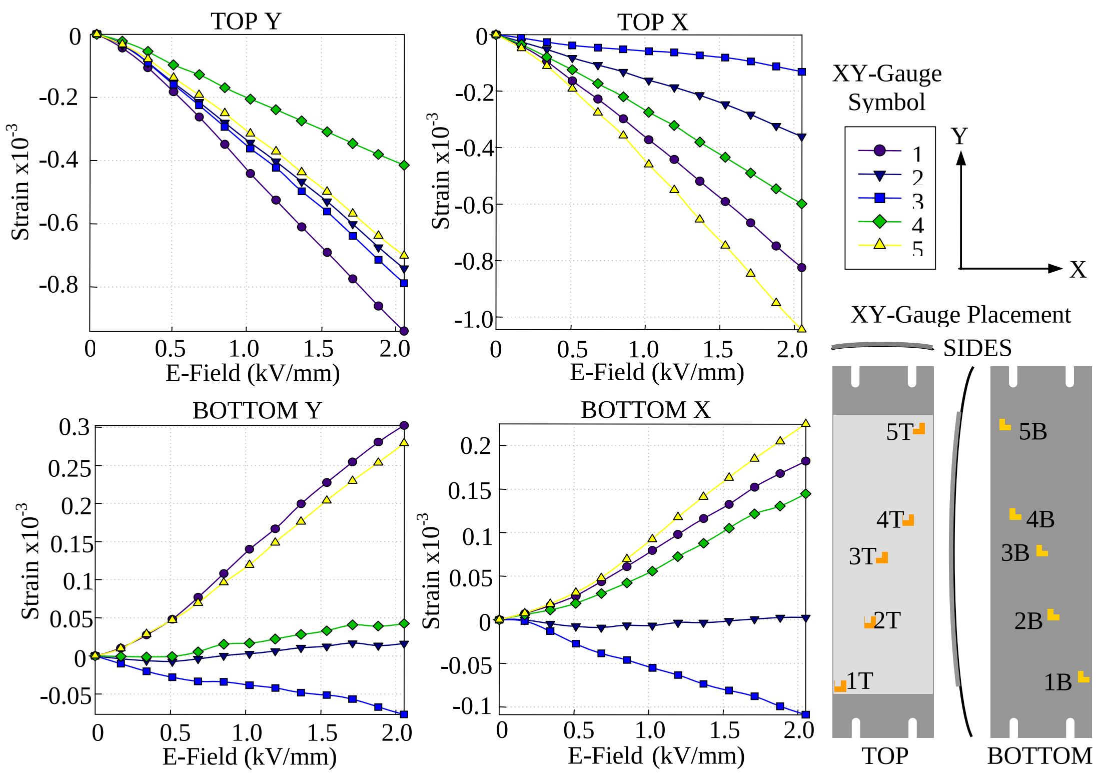


Figure 7. Strain vs. Voltage for a Typical THUNDER Wafer.

The amount of strain is a function of gauge location, fixturing and the selection of the layers of material creating the actuator. The actual displacement, which is a function of strain, is also a function of the length and width of the actuator. The higher the aspect ratio and length, the greater the center displacement.[8] This type of actuator has proved difficult to model computationally because of the high degree of non-linearity of the strain, due to loading and boundary conditions.[13-16] Typical center and cantilevered displacement for a 63.5 mm long THUNDER wafer is 0.4 and 2 mm respectively.[17] The strain field plots for a typical RFD are shown below on Fig 8. Here, XY strain gauges were placed radially and tangentially on the RFD from near center outwards, with two additional gauges on the polymer film beyond the sandwiched piezo-ceramic as indicated by the ceramic/film boundary.

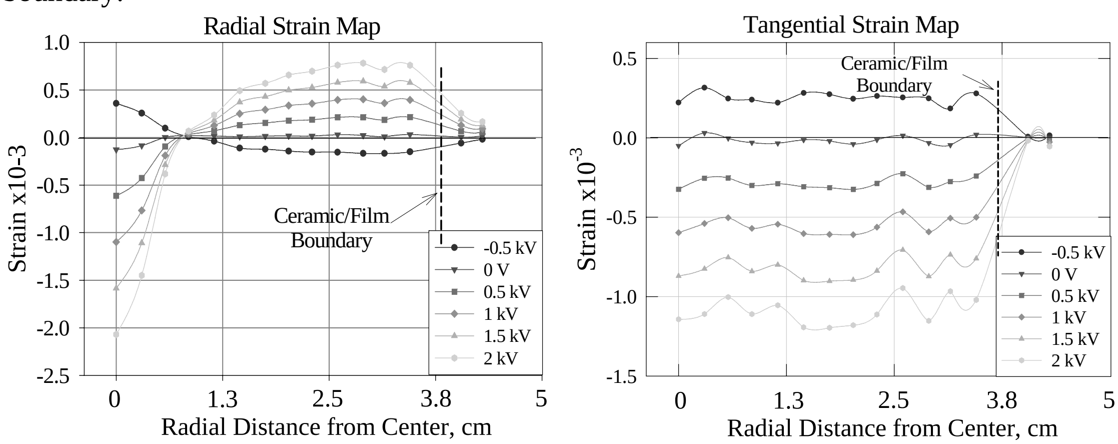


Figure 8. Strain at Indicated Voltage vs. Distance from Center for a Typical RFD.

What is interesting is that the strain not only changes sign, but has an inflection and drops to nearly zero at the edge of the ceramic indicating the RFD is self constrained along its edge. The typical low frequency center displacement for a 5 cm diameter x 175 μm thick PZT-5A ceramic RFD is ~0.8 mm.[7]

### 3.3. Application Examples

The advantages of using these higher displacement actuators in certain applications are that they consume less power; weight less; are simple in design, do not generate any electromagnetic interference (EMI), and are inherently radiation resistant. The packaging also protects the actuator material to the point that physical ceramic failures are rarely catastrophic. The disadvantages are that there is no historical data to indicate the reliability of system level hardware, and miniaturized control circuitry lags behind actuator development, especially for commodity components needed for higher voltages. However, design and system testing continue. Some of the working demonstrator prototypes for these NASA actuators are shown figs 9-11.


Figure 9. (a) THUNDER linear spectrometer motor, (b) Diesel valve injector actuator/sensor (c) THUNDER powered robot.

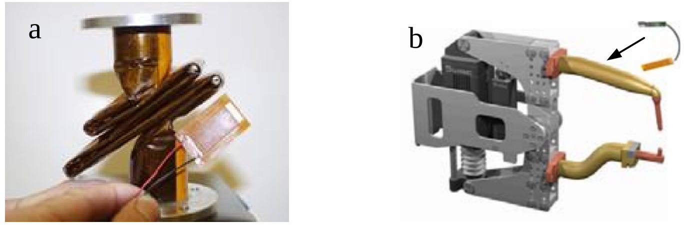


Figure 10. (a) RIGIX experimental inflatable tube with MFC vibration suppressor, (b) SWAC Gmbh. robotic welding head with MFC sensor pack.

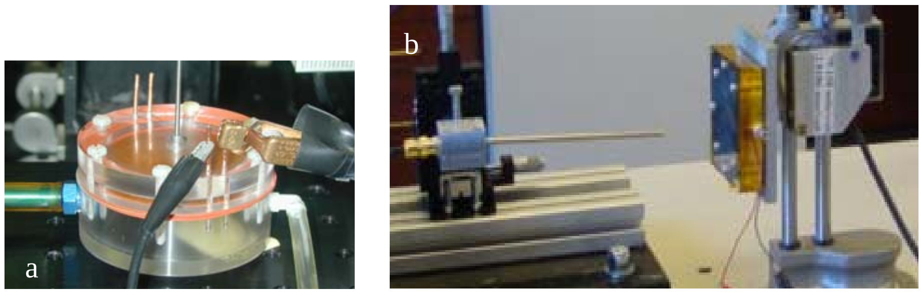


Figure 11. (a) RFD Diaphragm pump, (b) Synthetic jet with RFD driver.

## 4. CONCLUSION

The piezoelectric actuator packaging technology that NASA LaRC has refined by applying common manufacturing techniques to lower costs and increase quality has resulted in continuous research activity since their inception. The outcome is that the risk of developing applications has moved from the actuator to the system. This has also spurred the development of microelectronic control systems and numerous other applications that are being prototyped and commercialized for many piezoelectric devices. To date, there are over 150 technical publications relating to these three NASA actuator technologies, excluding the patent literature. The continued growth of the NASA based actuator technology is illustrated in Fig. 12, showing that industrial partners are currently supplying these actuators to customers worldwide because of their performance, adaptability, ease of manufacture and implementation, and availability.

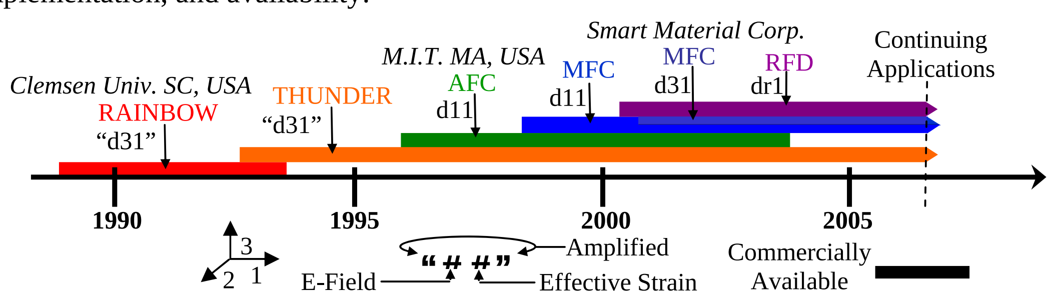


Figure 12. Timeline of post 1985 Piezoelectric Actuators.

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