JOURNAL OF MATERIALS SCIENCE **36** (2001) 4231 – 4237

Fabrication and experimental characterization of d_{31} telescopic piezoelectric actuators

PAUL W. ALEXANDER*, DIANN BREI*, WEIGUO MIAO†, JOHN W. HALLORAN†
*Departments of *Mechanical Engineering and Applied Mechanics and †Materials Science and Engineering, University of Michigan, Ann Arbor, MI 48109, USA*
E-mail: dibrei@engin.umich.edu

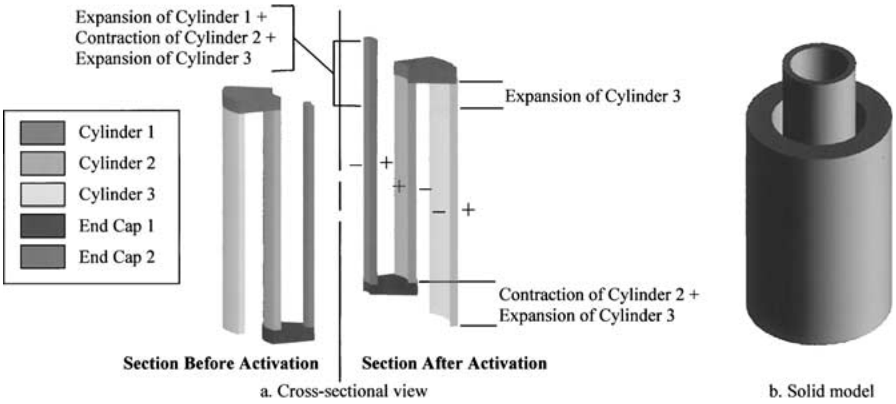
RICHARD L. GENTILMAN, GERALD E. SCHMIDT, PATRICK T. McGUIRE, JOHN R. HOLLENBECK
Materials Systems Inc., Littleton, MA 01460, USA

A popular and useful piezoelectric actuator is the stack. Unfortunately with this type of actuation architecture the long lengths normally required to obtain necessary displacements can pose packaging and buckling problems. To overcome these limitations, a new architecture for piezoelectric actuators has been developed called telescopic. The basic design consists of concentric shells interconnected by end-caps which alternate in placement between the two axial ends of the shells. This leads to a linear displacement amplification at the cost of force; yet the force remains at the same magnitude as a stack and significantly higher than bender type architectures. This paper describes the fabrication and experimental characterization of three different telescopic prototypes. The actuator prototypes discussed in this paper mark a definitive step forward in fabrication techniques for complex piezoceramic structures. Materials Systems, Inc. has adapted injection molding for the fabrication of net shape piezoceramic actuators. Injection molding provides several advantages over conventional fabrication techniques, including: high production rate, uniform part dimensions, uniform piezoelectric properties, and reduced fabrication and assembly costs. Acrylate polymerization, developed at the University of Michigan, is similar to gelcasting, but uses a nonaqueous slurry which facilitates the production of large, tall, complex components such as the telescopic actuator, and is ideal for the rapid manufacture of unique or small batch structures. To demonstrate these fabrication processes a five tube telescopic actuator was injection molded along with a very tall three tube actuator that was cast using the acrylate polymerization method. As a benchmark, a third actuator was built from off-the-shelf tubes that were joined with aluminum end-caps. Each prototype's free deflection behavior was experimentally characterized and the results of the testing are presented within this paper.

1. Introduction

The fabrication of piezoceramic actuators has historically depended on the assembly of simple discrete components to construct actuators capable of amplifying the limited strain produced by the material. For example, stacks are composed of multiple, thin layers of piezoceramic, each individually electroded and then bonded together. Benders are composed of two or more layers of piezoceramic bonded together or bonded to an inactive substrate. Fortunately, piezoceramic processing technology has made great strides in the last few years. For example, stacks can now be co-fired [1]; benders can be made using rainbow [2] or thunder technology [3] or functionally gradient materials [4–6]. Very complex shapes can be fabricated using solid freeform fabrication [7] or injection molding [8]. Even micro actuators with very large aspect ratios can be fabricated using microextrusion [9].

These advances in processing technology open the door for actuation designers since they are no longer restricted to simple geometric shapes. One particular actuation architecture that has benefited is the telescopic actuator developed by the Naval Research Laboratory. This architecture was created to generate forces of the same order of magnitude as stack actuators, while producing 1–20 times the displacement of a similar length stack. This aids in those applications that would require very long stacks because of stroke requirements, which could experience problems such as buckling. A telescopic actuator is composed of multiple nested shells interconnected by end-caps alternating in placement between the two axial ends of the shells (Fig. 1). The shells are activated in an alternating manner, resulting in the expansion (contraction) of one cylinder while the adjacent cylinders contract (expand); thus, the architecture "telescopes" outward



a. Cross-sectional view

b. Solid model

Figure 1 Operation of a telescopic actuator—cylinders alternate in expansion and contraction, thereby telescoping out.

(inward), producing useful amounts of work in the axial direction.

Although it is possible to construct a telescopic actuator by connecting individual tubes with discrete end-caps, current processing technologies make it feasible to construct a monolithic structure. Obviously, there are advantages to utilizing these solid-state processing techniques, such as decreased production time, reduced number of components and elimination of losses in discrete end-caps and bonding layers. Though the advantages of the telescopic architecture can be reaped in both the d_{33} and d_{31} modes of activation, all the actuators discussed in this paper utilize the d_{31} mode of actuation. All of the cylinders are poled in the radial direction and are activated such that each cylinder is driven with a radial potential opposite the potential of the adjacent cylinder. This paper presents two novel fabrication processes well suited to the construction of very complex ceramic structures: injection molding and acrylate polymerization. To demonstrate the capabilities of these manufacturing techniques, monolithic piezoceramic telescopic actuators were created. Experimental results are given for several d_{31} telescopic prototypes built using the new processes along with a baseline actuator built from discrete components and end-caps.

2. Injection molding

Injection molding is widely used in the plastics industry as a means for rapid mass production of complex shapes at low cost. It has been adapted for the fabrication of net shape piezoceramic actuators to provide several advantages over conventional fabrication techniques, including: high production rate, uniform part dimensions, uniform piezoelectric properties, and reduced fabrication and assembly costs. Ceramics injection molding was recently demonstrated as a low cost method for fabricating and simultaneously aligning thousands of identical PZT rods to produce highly repeatable, low-cost 1–3 piezocomposites for medical imaging and Navy undersea applications [10]. It is now being adapted for the fabrication of a telescoping tube actuator that is difficult to produce by conventional techniques, such as isostatic pressing, machining, or slip casting [11].

The basic injection molding process used by Materials Systems Inc. (MSI) for PZT transducer fabrication is shown schematically in Fig. 2 [8]. Materials Systems' injection molding process utilizes a heated thermoplastic mix of PZT powder and a wax-based binder. The binder in the mixture acts as a carrier during molding, allowing the material to be transferred as a viscous fluid when subjected to heat and pressure. The hot thermoplastic mixture of ceramic powder and organic binder is forced into a cooled mold creating a net shape green part (Fig. 3). The molded part is subsequently heated slowly in air to remove the organic binder. The PZT shape is then sintered at 1250°C for 1 hour, under controlled atmospheric conditions to achieve the desired piezoelectric properties.

Fig. 4 is an example of a telescopic actuator consisting of five nested ceramic tubes with five integrated monolithic end-caps. By designing the mold cavity to achieve the final actuator dimensions (18.5 mm O.D. × 25 mm overall length), no further assembly or machining is required (Fig. 5). Each sintered part is subsequently contact poled in five steps (one tube at a time) using a field of 1.2 kV/mm through the wall thickness to achieve a positive polarity on the inner diameter of each tube. After poling, a permanent nickel electrode is applied to all surfaces of the actuator. The four end-caps that connect adjacent tubes and the one that bridges the inner tube, as seen in Figs 4 and 5, isolate the positively and negatively charged surfaces and allow for the continuous electroding process. However, the electrode layer on the bottom ring of the outer tube must be ground off so that two distinct electrodes are created; to which, wires are attached for the purpose of activation (Fig. 6). This arrangement reverses the electric field that is applied to the second and fourth tubes, causing the structure to "telescope" during actuation.

MSI formulates its own piezoelectric compositions for enhanced piezoelectric performance, and the injection molding and proprietary sintering processes ensures a uniform and defect-free microstructure (Fig. 7). Because the process utilizes a liquid feed stock injected under high pressure, the macroscopic voids often associated with traditional dry powder processing are eliminated. Furthermore, the isostatic nature of the process produces a very uniform green microstructure and green density; therefore, subsequent densification leads to uniform mechanical properties and part dimensions. PZT components routinely exceed a density of 7500 kg/m^3 (approaching the theoretical maximum density). MSI-53HD ceramic's d_{33} piezoelectric

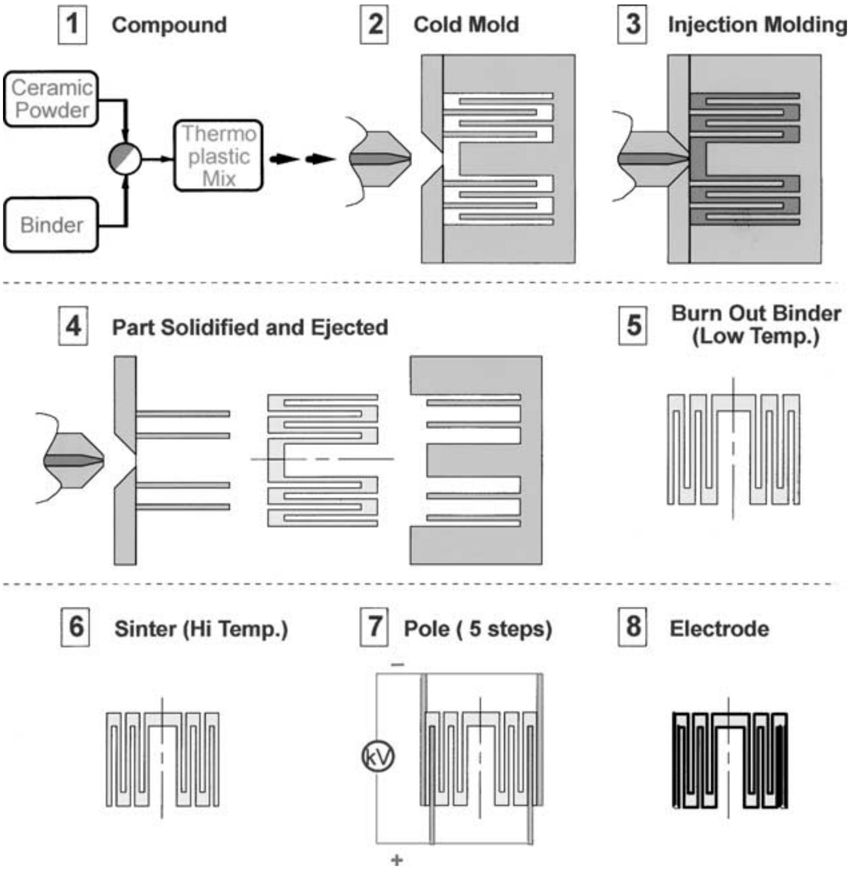


Figure 2 Schematic description of injection molding process—(1) Hot wax-ceramic mixture in nozzle. (2) Injection of mix into mold. (3) Mix cools and forms solid part. (4) Net shape green part is ejected from mold. (5) Green part is heated slowly in air to remove organic binder. (6) PZT shape is sintered in a controlled atmosphere. (7) Sintered PZT shape is contact poled in oil. (8) Permanent electrode is applied.

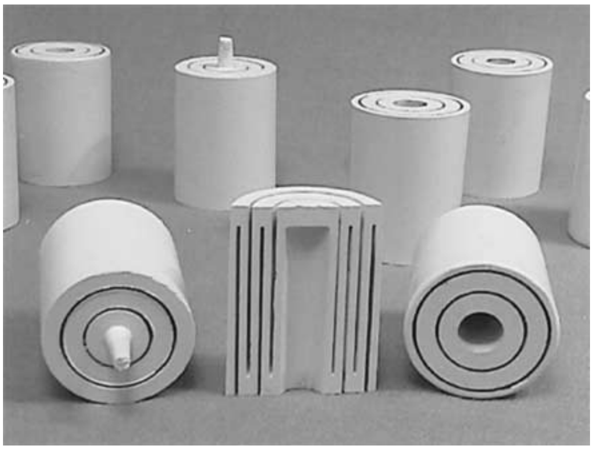


Figure 3 Green parts—net shape injection molded wax-ceramic preforms.

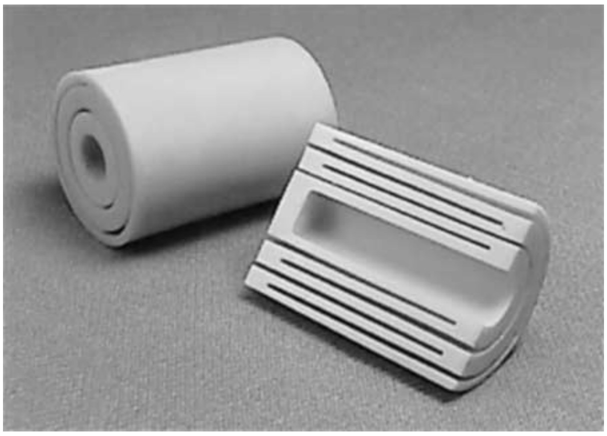


Figure 4 Sintered actuators—net shape ceramic preforms shown after sintering.

coefficient was measured to be 725 pm/V, which is similar to the MSI-53 used to fabricate the telescoping tube actuators.

3. Acrylate polymerization

Polymerization is another novel technique that can be employed for the fabrication of complex ceramic shapes by the molding of, or solid freeform fabrication of a polymerized ceramic slurry [12]. Most of the research into this polymerizing procedure has been focused on aqueous polymerization where the solvent utilized is water [13–15]. Aqueous polymerization produces a green body that is relatively soft and fragile, which leads to problems removing the structure from the mold prior to the drying process. A process which uses a nonaqueous slurry is described here that will produce a green ceramic body that is much more durable, thus facilitating the demolding procedure. This makes it optimal for rapid production of one-of-a-kind, large complex ceramic structures, such as the telescopic actuator prototype.

The proper slurry composition is crucial to this fabrication process. The slurry's main ingredient is PZT

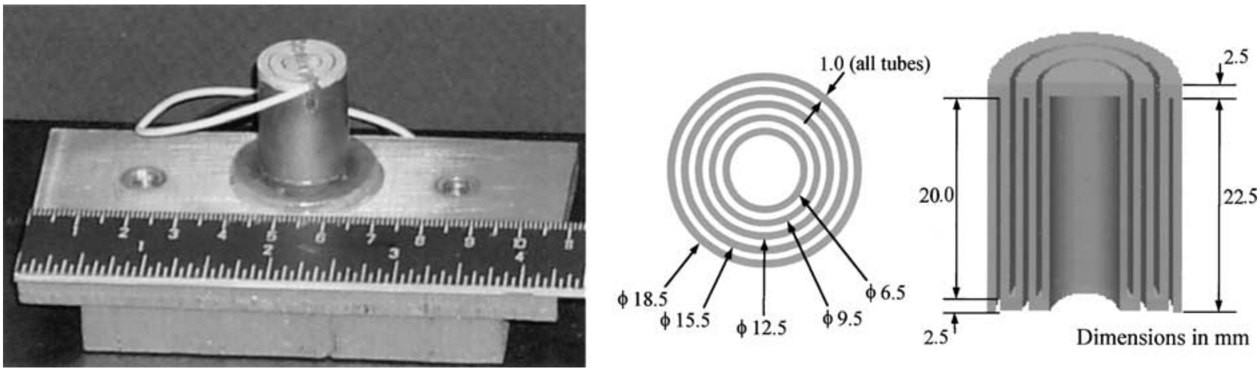


Figure 5 Injection molded MSI-53 actuator—photograph and schematic.

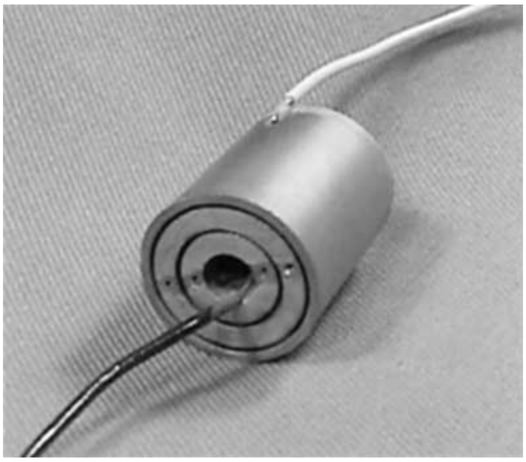


Figure 6 Finished actuator—after poling, electroding, and wiring.

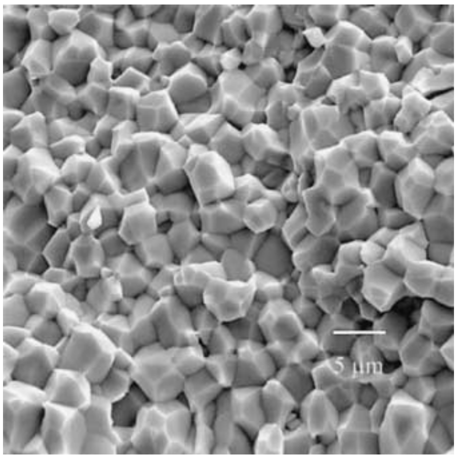


Figure 7 Injection molded fracture surface—MSI-53 ceramic.

586 powder, obtained from American Piezo Ceramics, Inc. (similar to PZT 5A) with a median particle size of 1.1 μm. This powder is mixed with the difunctional monomer propoxylated neopentyl gycol diacrylate (PNPDGA, Sartomer) and the monofunctional monomer 2-(2-ethoxyethoxy) ethyl acrylate esters (EOEOEA, Sartomer). The system solvent, decahydronaphthalene (decalin, Avocado), was also added to the mixture, as was the dispersant, 1 wt% Emcol CC-55 (Witco Corp.), which ensures the PZT powder remains in suspension. The resulting slurry has a high solid load of 51 vol% PZT, but is fluid enough to easily fill a mold. Polymerization of the acrylate monomers is initiated with 0.1 wt% Benzoyl peroxide (BPO, Aldrich) and 0.025 wt% *N*,*N*-dimethyl-*p*-toluidine (DMPT, Aldrich) is added as a catalyst to lower the curing temperature.

The slurry described above remains workable for approximately ten minutes, during which time the casting process must be completed. In this case, the slurry was simply poured into a mold and allowed to cure at room temperature. The molds used to fabricate the telescopic actuator prototype were made from an epoxy resin utilizing a stereolithography technique. A computer-designed two-piece mold was created, which produced a 75.2 mm tall, three tube, cylindrical telescopic actuator with 1.2 mm wall thickness (Fig. 8). To facilitate demolding, the SLA molds were carefully polished and lubricated prior to use. After the curing process was completed, the green ceramic actuator was carefully removed from the mold. The use of a nonaqueous slurry makes the removal step easier. The resulting telescopic actuator in its green state is shown in Fig. 9. The polyacrylate binder is removed by slowly heating in air. After polymer burnout, the actuator is still relatively fragile and the individual grains of the PZT must be sintered together to impart structural rigidity. The part is heated up to 1275°C where it is sintered for 4 hours in

Figure 8 SLA mold—two piece, three tube actuator mold.

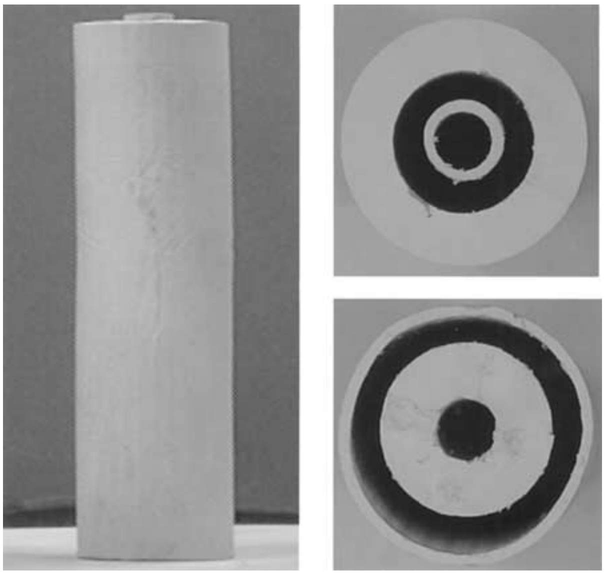


Figure 9 Green part—polymerized actuator preform.

a PbO rich atmosphere. The actuator is finished by applying silver paint for electrodes and poling it at 2000 V (1.67 MV/m) in a 160°C silicone oil bath. The resulting telescopic prototype is shown in Fig. 10.

This fabrication procedure produced PZT of extremely high quality. The material showed a large amount of densification, as illustrated in the micrograph of Fig. 11. The density was greater than 98% of the theoretical. This compares favorably with commercially fabricated PZT, whose densities are around 95–96% of theoretical. The piezoelectric properties were also higher than expected, yielding d_{33} values of 680 pm/V as opposed to the expected value of 590 pm/V for PZT586. Thus, this acrylate polymerization procedure is indeed capable of producing high quality ceramic structures of complex shape.

4. Conventional component assembly

As a baseline, a third telescopic actuator prototype was constructed from off-the-shelf piezoceramic tubes and aluminum washer-like end-caps. The piezoceramic tubes were APC's 855 composition, similar to PZT 5H. The three tubes used to build the actuator were all of a length of 76.0 mm, a thickness of 1 mm, and outer diameters of 25.4 mm, 19.1 mm, and 12.7 mm. The tubes were linked together by two aluminum end-caps, each 3.2 mm thick, as shown in Fig. 12. The components were bonded together using a two part epoxy from Insulcast (Insulcure 24, Insulcast 501). The actuator was completed by wiring adjacent tubes with opposite polarity.

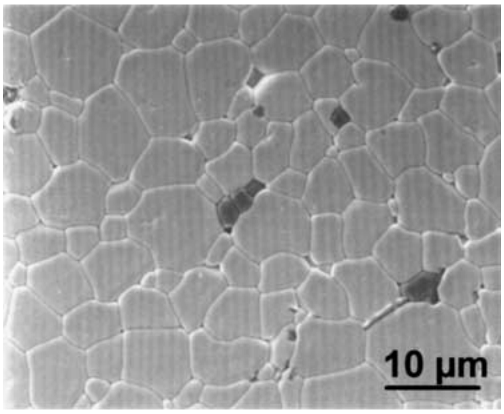


Figure 11 Polymerized PZT586 micrograph—low porosity piezoceramic.

5. Experimental characterization

To assess the different fabrication methods, the free deflection performance of each prototype was experimentally measured utilizing the experimental setup depicted in Fig. 13. Each prototype was mounted on an aluminum plate and secured with a vise. A thin square of aluminum was bonded to the inner most tube of each actuator to serve as a reflective surface to facilitate readings using a Philtec fiber optic displacement sensor. The sensor was monitored with a Fluke digital multimeter. The actuators were activated using a Kepco DC power supply in 50 volt increments. At each increment the displacement was measured with the fiber optic probe. This process was repeated until the maximum applied

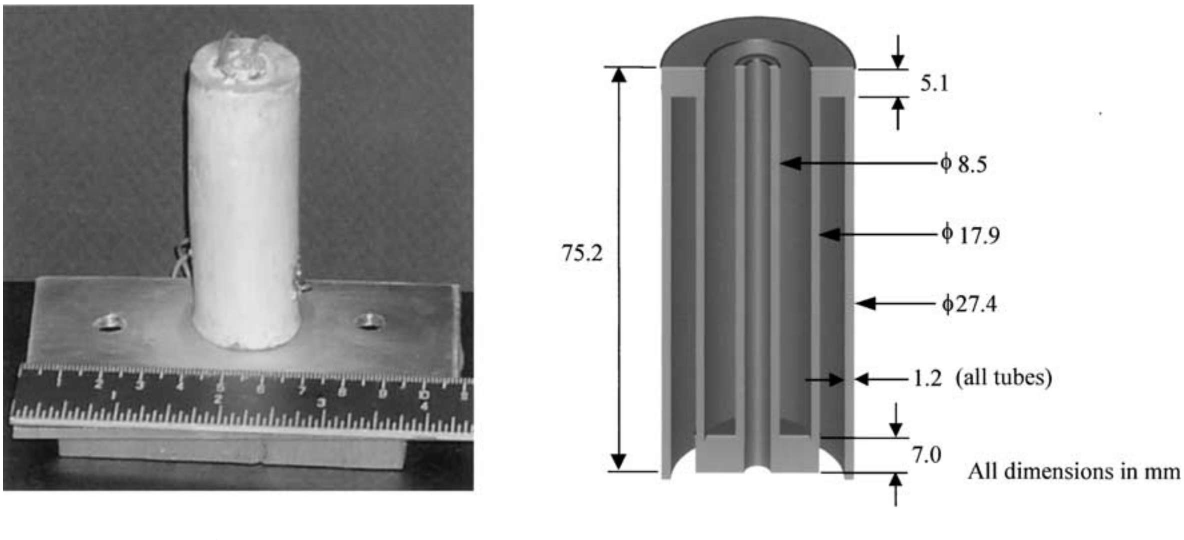


Figure 10 Polymerized PZT586 actuator—photograph and schematic.

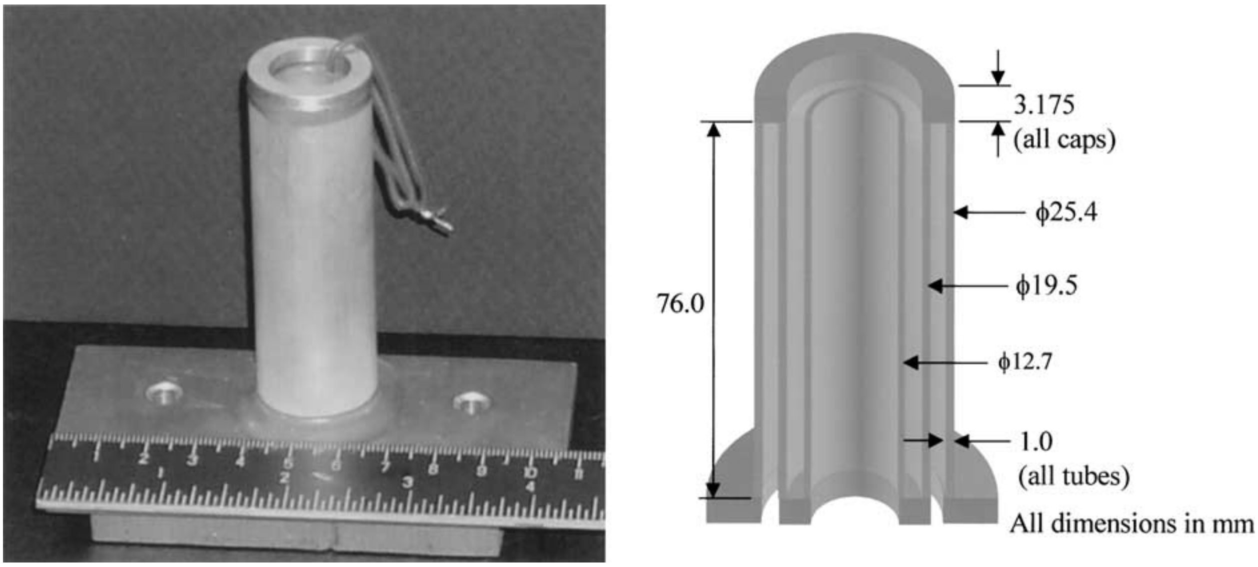


Figure 12 Conventionally assembled component actuator—photograph and schematic.

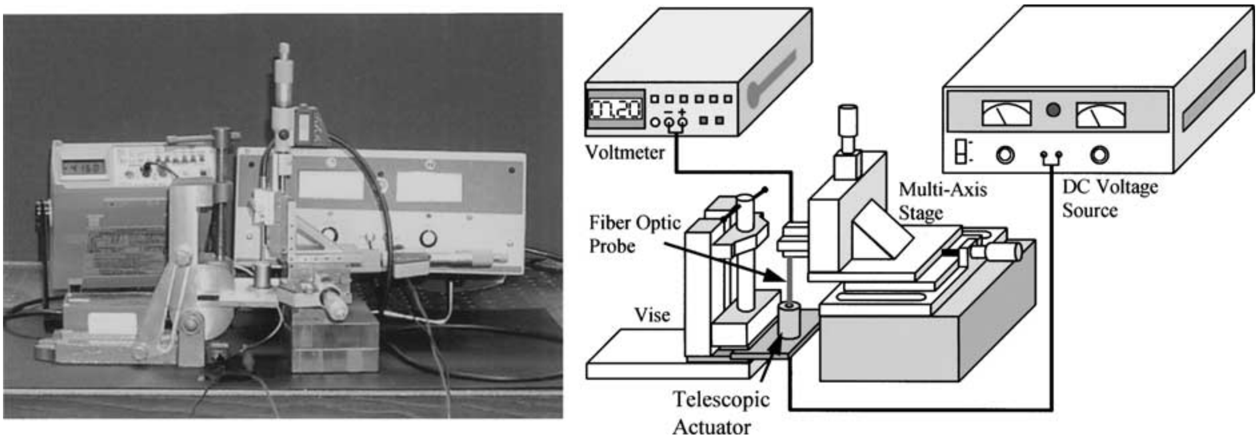


Figure 13 Experimental test apparatus—photograph and schematic.

DC voltage was reached, 300 V for the two monolithic actuators and 400 V for the baseline actuator. Once the maximum field was reached, the voltage was stepped down, again in 50 volt increments, until zero volts was reached. At this point the leads from the power supply were reversed and the process was repeated for negative voltages.

The experimental results for each of the three actuators when driven to their maximum allowable field are given in Fig. 14. The injection molded actuator produced a maximum deflection of 14.72 μm when subjected to an electric field of 300 kV/m. The polymerized telescopic prototype, activated by 250 kV/m, produced 24.69 μm of deflection. And lastly, the conventionally assembled actuator exhibited a maximum deflection of 33.17 μm when placed in a 400 kV/m electric field. The average displacement of each prototype when driven to 250 kV/m is 11.63 μm for the injection molded actuator, 24.69 μm for the polymerized prototype, and 22.53 μm for the conventionally assembled actuator. The corresponding resultant strains (deflection/length of actuator) are 465 $\mu\varepsilon$, 328 $\mu\varepsilon$, and 284 $\mu\varepsilon$ for the injection molded, polymerized, and conventional actuators respectively.

Since the prototypes were manufactured with different material characteristics and physical dimensions to highlight strengths of each fabrication process, it is not reasonable to compare the prototypes to one another. However, they can be compared individually to the theoretically predicted performance [16]. Using linear piezoelectric theory, the free deflection of a telescopic actuator is simply the sum of the individual displacements from each cylinder, given by:

$$\Delta = \sum_{i=1}^{n} d_{31_i} \frac{V}{t_i} L_i \tag{1}$$

Where Δ is the deflection, n is the number of tubes in the actuator, d_{31_i} is the ith tube's piezoelectric coefficient, V is the applied voltage, t_i is the ith tube's thickness, and L_i is the ith tube's length. For the injection molded prototype, an experimentally measured d_{31} value of 440 pm/V was employed in the model, yielding a maximum theoretical deflection of 14.99 μm. The average error for this prototype was determined to be 13.4%, but this is mainly due to hysteresis, which reached a maximum of 6.56 μm. The error at the maximum free deflection (14.72 μm), where there is little hysteresis, was only 1.8%.

The experimentally determined d_{31} value for the polymerized actuator was 430 pm/V, which gave a predicted maximum deflection of 21.93 μm, resulting in

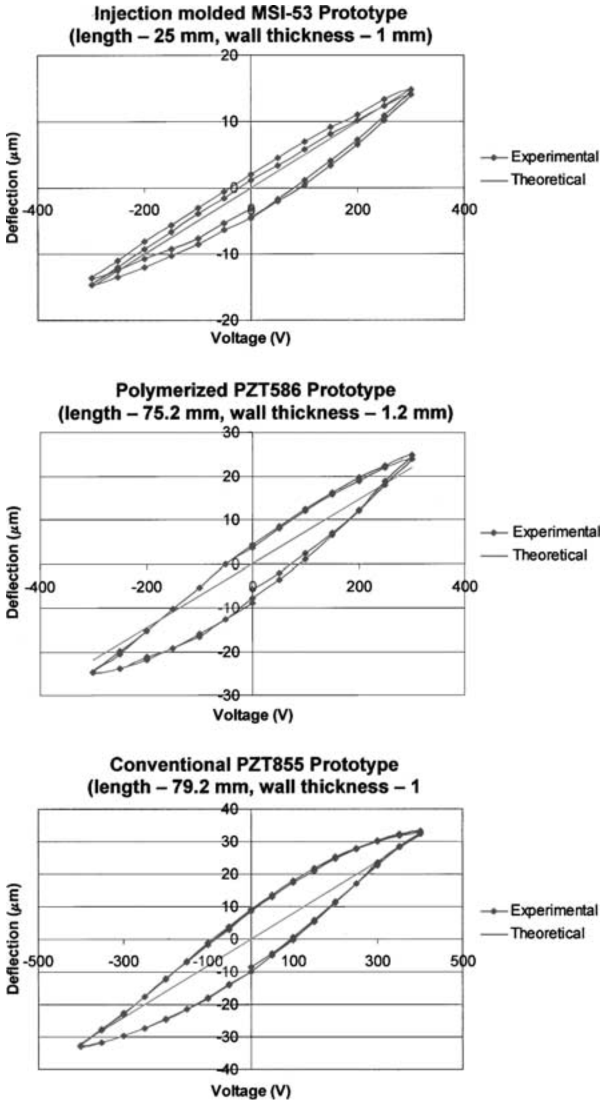


Figure 14 Deflection-Voltage experimental results.

12.6% error when compared to the measured maximum deflection of 24.69 μm. It should be noted that the increased error in this case most likely stems from uncertainty in the electroded length of the polymerized actuator's cylinders. For the polymerized telescopic actuator, the average error in the model was 20.5%; again, mostly due to hysteresis, which peaked at 11.47 μm.

For the baseline prototype, the maximum free deflection, 33.17 μm, correlated well with the theoretical value of 31.92 μm, to within 3.9% when using the measured d_{31} value of 420 pm/V. The maximum hysteresis was 19.07 μm, and the average error in the model was 18.2%. It is relevant to once again point out that the linear nature of the theoretical model does not attempt to capture the hysteresis that all piezoceramics exhibit; but, as evidenced in Fig. 14, when hysteresis is taken into account, the experiments do track the model well.

6. Conclusions

This paper describes two novel manufacturing techniques, injection molding and acrylate polymerization, each of which were used to fabricate a monolithic telescopic actuator. Such an actuator is complex and would be very difficult to construct using conventional techniques such as isostatic pressing or slip casting. Both of these techniques produced quality piezoceramic parts with high densities and piezoelectric properties. Injection molding is best suited to producing complex structures of moderate height in large volumes where cost is a definite factor. Acrylate polymerization is better suited to fabricating tall or large structures in smaller quantities, and is ideal for the rapid prototyping of complex ceramics. The analytically derived linear model correlates well with the deflection-voltage behavior of all three telescopic prototypes, regardless of the actuator geometry, fabrication process employed, or construction materials. This paper demonstrated the viability of fabricating large monolithic telescopic actuators.

Acknowledgments

This research was supported by DARPA, the Defense Advanced Research Projects Agency (Grant # N00014-97-1-G009), the Office of Naval Research, and the Naval Research Laboratory.

References

1. K. BRIDGER, L. JONES, F. POPPE, S. A. BROWN and S. R. WINZER, Smart Structures and Materials: Industrial and Commercial Applications of Smart Structures Technologies, San Diego, CA, 1996, p. 341.
2. G. H. HAERTLING, *American Ceramic Society Bulletin* **73** (1994) 93.
3. C. SHAKERI, C. M. BORDONARO, M. N. NOORI and R. CHAMPAGNE, Proceedings of the Smart Structures and Materials Conference, Newport Beach, CA, 1999, p. 63.
4. C. C. M. WU, M. KAHN and W. MOY, *J. Amer. Ceram. Soc.* **79** (1996) 809.
5. X. ZHU, Q. WANG and Z. MENG, *J. Mater. Sci. Lett.* **14** (1995) 516.
6. R. K. PANDA, A. L. KHOLKIN and A. SAFARI, in Proceeding of the 11th IEEE International Symposium on Applications of Ferroelectrics, Montreaux, Switz., 1998, p. 265.
7. A. SAFARI and S. C. DANFORTH, in Proceeding of the 11th IEEE International Symposium on Applications of Ferroelectrics, Montreaux, Switz., 1998, p. 229.
8. L. BOWEN and K. FRENCH, in Proceedings of the 8th IEEE International Symposium on Application of Ferroelectrics, Greenville, SC, 1992, p. 160.
9. A. T. CRUMM and J. W. HALLORAN, *J. Amer. Ceram. Soc.* **81** (1998) 1053.
10. R. L. GENTILMAN, D. F. FIORE, H. T. PHAM, K. W. FRENCH and L. J. BOWEN, *Ceramic Transactions* **43** (1994) 239.
11. J. S. REED, *Ceramic Transactions: Ceramic Powder Science IIB* **1** (1988) 601.
12. K. VENKATASWAMY, R. WAACK, B. E. NOVICH and J. W. HALLORAN, US Patent no. 4978643 (1990).
13. G. T.-M. CHU, G. A. BRADY, W. MIAO, J. W. HALLORAN, S. J. HOLLISTER and D. BREI, "Solid Freeform and Additive Fabrication," edited by D. Dimos, S. C. Danforth and M. J. Cima, MRS Symposium Proceedings, Vol. 542, 1999, p. 119.
14. O. O. OMATETE, M. A. JANNEY and R. A. STREHLOW, *Ceramics Bulletin* **70** (1991) 1642.
15. M. A. JANNEY, O. O. OMATETE, C. A. WALLS, S. D. NUNN, R. J. OGLE and G. WESTMORELAND, *J. Amer. Ceram. Soc.* **81** (1998) 581.
16. D. BREI and N. T. BERNER, in Proceedings of the ASME International Mechanical Engineering Congress and Exposition—Adaptive Structures and Material Systems, Nashville, TN, 1999, p. 189.

Received 21 March
and accepted 9 October 2000