

A Survey and Comparison of Smart Material Linear Actuators

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1. SCOPE OF RESEARCH

The basic types of smart material actuators are first reviewed. The actuators are then compared based on four main characteristics: size, force, displacement, and frequency range. One goal of this research is to reduce the time designers normally spend selecting actuators based on these characteristics. Much time and effort can be spent contacting numerous and various actuator companies for specific data. Further, it requires additional effort to learn each actuator's fundamentals and performance parameters. We have attempted to simplify and speed up this process by collecting data from a variety of vendors, manufacturers, and research publications.

2. MOTIVATION – A BETTER DESIGN TOOL

In the design process, engineers must be able to understand their options for mechanical actuation. Actuators are the key drivers in any machine or mechanism; they are the point at which energy is converted into force and motion. When designing for a particular application, several key parameters are specified, including output force, displacement, and frequency. Size and power constraints may also be specified. Based on these few parameters alone, it is desired to be able to look at the vast array of existing actuators and see which candidates match. It is important to realize the entire spread of possibilities and alternatives to meet the requirements of a given application.

This research focuses on a more applied and less fundamental approach to actuator comparisons. As mentioned, comparisons based directly on design parameters will be more useful in the design process. In performing the comparisons, one of the key objectives is to include size (either mass or volume), so the effects of scaling can be observed. It is well known that scaling can have a large effect on some actuation schemes. For the designer who works in several domains (e.g. micro and macro devices) this information is important.

3. BASIC ACTUATOR TYPES

3.1. PIEZOELECTRIC

Piezoelectric actuators are small-scale, stiff, load-bearing, stackable actuators. They are the most commercialized and understood technology in the smart actuator market. While also used for sensors, the more relevant application is in actuation, for which the most common materials are piezoceramics. The most popular piezoceramic material is lead zirconate titanate (PZT).

3.1.1. *Principle*

Piezoceramics experience mechanical deformations in electric fields, providing a means of actuation. The internal crystal structure of a piezoceramic has no center of symmetry. Therefore, when ions are displaced in the anisotropic crystal lattice by an outside electric field, the material is polarized. This displacement of charge is coupled to a displacement in the lattice structure. The sum of these displacements result in bulk deformation of the material.

3.1.2. *Advantages*

These actuators typically provide displacements from 0.001 to 0.002 strain (0.1-0.2%). Their large bandwidth is another great advantage; operation in the gigahertz frequency range is even possible. They have good linearity, a low thermal coefficient, and since they are electrically driven, can be directly integrated with the operating electronics. The devices and material are moderately priced compared to other actuators. Piezoceramics weigh near 7.5-7.8 g/cm³ and have a maximum operating temperature near 300°C [1].

3.1.3. *Disadvantages*

The main disadvantage of piezoelectric actuators is the high voltage requirements, typically from 1 to 2 kV. Further, as the size of the actuators increases, so does the required voltage, making them favorable only for small-scale devices. Being ceramic, PZT actuators are also brittle, requiring special packaging and protection. Other disadvantages are the high hysteresis and creep, both at levels from 15-20%.

3.1.4. *Typical Uses*

Due to their fundamental operating principles, the typical and practical applications of piezoceramics are for dynamic strains and of an oscillatory nature. These include microphones, relays, and strain gages. Piezoelectric actuators are also used for positioning the heads in scanning tunneling microscopes, thereby taking advantage of the actuator's fine positioning capabilities.

3.1.5. *Single-crystal Piezoceramics*

Still in development, and offering great improvements, are single-crystal piezoceramics. They are costlier to manufacture than current piezoelectrics, but offer lower hysteresis at 10-15% and 5 to 10 times greater strain [2].

3.2. MAGNETOSTRICTION

Magnetostrictors are large-scale, high-force, and high-stiffness actuators. They derive their actuation from the elongation they experience in the direction of a uniform longitudinal magnetic field.

3.2.1. *Principle*

The dimensional change of magnetostrictors is explained at the atomic level. Small internal magnetic domains rotate to align with the applied magnetic field. The distortion of the crystal structure from random to aligned provides “proportional, positive, and repeatable expansions within microseconds.” [3] Because the displacement per unit magnetic field increases with dimension, magnetostriction favors large-scale, heavy-duty actuators.

3.2.2. *Advantages*

Terfenol-D, developed by the Navy, is the most popular magnetostrictor material. It is composed of terbium, iron, and the expensive, rare-earth dysprosium. Strains of 0.1 to 0.6% can typically be obtained, with operating frequencies from 0 to 30 kHz. Not only do they exhibit good linearity, but a moderate level of hysteresis at 2%. Applications typically involve displacements from 0.008-10 mm. The material weighs about 9 g/cm³ and has a maximum operating temperature near 400°C [1].

3.2.3. *Disadvantages*

A primary disadvantage of magnetostrictors is the need for delivery of a controlled magnetic field to an embedded actuator. Additionally, magnetostrictive materials produce greater responses under compressive loads, creating further interaction with the application. Planning and accounting for this unknown interaction may be difficult. Finally, magnetostrictors require more power than piezoelectric actuators.

3.3. ELECTROSTRICTION

Electrostrictive actuators function similarly to magnetostrictors, but have applications more similar to those of piezoceramics. Their prime difference from piezoceramics is that electrostrictors only experience elongations regardless of the direction of the applied electric field, while piezoceramics can exhibit bi-directionality.

3.3.1. *Principle*

The strain in electrostrictors results from deformation due to a field gradient, but not a direct polar strain. Rather, individual polar, micro-domains within the ceramic rotate to align with an electric field, analogous to the rotation of magnetic micro-domains in magnetostrictors. The electrostrictive effect is present in all materials, but only those with a giant effect (>0.7 nm/V) are useful as actuators [4].

3.3.2. *Advantages*

Electrostrictors can provide 0.1 to 0.2% strain and operate from 20 to 100 kHz. They have a low thermal coefficient (10⁻⁶ V⁻¹) and weigh near 7.8 g/cm³ [4]. The most common

electrostrictive materials are ceramics with operating temperatures near 300°C. Finally, their low hysteresis (<1%) makes them unique among most smart material actuators.

3.3.3. *Disadvantages*

The main disadvantage of electrostrictors is their inherent nonlinearity. From their constitutive equations, elongation follows a square law function of applied electric field (V/m). To compensate for this, voltage biasing is used to attain regions of nominal linearity [4].

3.3.4. *Typical Uses*

Again, electrostrictors and piezoceramics share similar applications. For example, an electrostrictor may provide 10 μm of displacement at 1 kV with an operating frequency greater than 20 kHz [4]. Like piezoceramics, these are also stackable, where a typical configuration may provide 15 μm of displacement with only 150 V applied voltage [4].

3.4. SHAPE-MEMORY ALLOYS

Shape-Memory Alloys (SMA) are low-stiffness, high-displacement, thermally-driven actuators. Being thermally activated, their response time is cooling dependent; thus SMAs are slow and unsuitable for high-frequency applications.

3.4.1. *Principle*

When plastically deformed, SMAs can recover their original state when heated above a specific transformation temperature. As this happens, phase-transformations occur in and out of a martensitic phase. These transformations occur with either mechanical loads or temperature, providing the opportunity for actuation. For one-way actuation, strains typically range from 4-6%. Materials can also be “trained” to work bi-directionally, but at the cost of reduced strains.

While speed is limited by heating and cooling and size is only limited by manufacturing capabilities, forces and displacements are governed only by a limit on overall power. This limit is typically near 1 in-lb/sec (0.1 Watt) [5]. SMAs can therefore theoretically provide infinitely high displacements (or forces), but at the tradeoff of either device size, near-zero force, (or near-zero displacement), depending on the arrangement. This relationship is visualized as the parallel curves seen in the actuator maps included later in this report.

3.4.2. *Advantages & Disadvantages*

In addition to greater strains than any other smart actuator, SMAs provide good linearity and remarkable simplicity. All that is required for a device is the material and a current source. On the other hand, they are slow with a maximum operating frequency between 0.5 and 5 Hz. Like most other smart materials, SMAs also have high hysteresis.

3.4.3. *Typical Uses*

The most popular SMA material is Nitinol, which is typically fabricated as a wire for actuator applications. Nitinol is low-cost, weighs about 7 g/cm³, and has a maximum operating

temperature near 300°C [1]. Wires can be fabricated down to 0.050 mm in diameter [5], and are often used as actuators in micro- and macro-scale robot arms.

Another means of actuation is realized by bonding SMA strips to strips of other materials, resulting in bi-material cantilevers akin to many existing thermal actuators. A typical example [6] may have an SMA cantilever 100 mm long that provides 20 mm of displacement and 300 N with a 4 second cycle time. Such devices have been used to align optical fibers in a circuit to within 100 nm.

3.5. FERROMAGNETIC SHAPE-MEMORY ALLOYS

Ferromagnetic Shape-Memory Alloys (FSMA) are a newer smart material. Their principle operation is similar to that of other SMAs, except that they are magnetically activated. They can experience up to 6% strain [3]. Since they are magnetically activated, they can be driven much faster than traditional SMAs for high-frequency response. These advantages come at the cost of the additional components required to provide the magnetic fields, whereas other SMAs only require a simple current source.

3.6. HYBRIDS & PUMPS

With some of the above actuator technologies being widely researched, several innovations and combinations of actuators have resulted in other interesting devices. Many combinations of actuators have been used in hybrid stepper drives [7]. These drives require three individual actuators, each with its own control signal. Two of the actuators serve as clamps, with an extensional actuator connected between them. While one end is clamped, the center section extends, and then the other end is clamped. The first end is then unclamped, and the center section shortens, bringing the first end one step forward. This process keeps repeating to create linear motion. Other combinations of actuators include a piezo-hydraulic pump, where piezoceramics are used to drive hydraulic fluid in and out of a cylinder [8]. Such a device demonstrates the ability to trade the small displacements and high-frequency of piezoceramics for large displacements at lower frequencies.

4. OTHERS ACTUATORS USED FOR COMPARISON

To give some reference while reviewing the various actuator maps below, other actuators are also being included for comparison. Hydraulic systems are typically heavy, large-scale, slow, high-force actuators, operated by the transfer of fluid to create pressure. Also included are electromagnetic drives, which consist both of electric motors, ball-screw drives, and linear stator/rotor trains. Electrostatic actuation, the most popular driving power in MEMS, is also of interest. These devices take advantage of the electrostatic “pull-in” attraction of parallel finger to create high-force, low-displacement motion under high applied voltages. Finally, muscle, biology’s prime actuator, is also included. Data is taken both from actual muscles and artificial muscle technology that is being investigated as a new source of actuation.

5. PREVIOUS ACTUATOR COMPARISON STUDIES

A number of charts and schemes have already been created for comparing a variety of actuators. Most of these efforts focus on normalized characteristics, such as stress (instead of

force) and “specific” properties such as energy density. While this information provides a good comparison of one actuator to another based on their intrinsic properties, the comparison is not with respect to any particular application. A few actuator companies [9][10], several universities [11][12][13], and the smart material general information website, www.intellimat.com, have provided examples of normalized comparisons.

There are several groups of researchers striving to even further classify actuators based on energy parameters. The smart materials research group at the Virginia Polytechnic Institute has published several papers on “Energy-based Comparisons of Actuators” [2][14][15], developing a method to classify and compare mechanisms based on various work and energy densities. Similar work has been performed at the University of Michigan [16]. While both of the above studies provide good energy and specific property comparisons, they do not contain the complete information a designer requires. When all the properties are normalized with respect to size and/or area, then the effects of scaling are not seen. Designers who work over a broad scale of design domains should be especially concerned with the extrinsic properties of actuators and how they change from one domain to another.

6. DATA SURVEY

The data for the comparison charts in the following sections of this report originate from many sources. Most of the data came from companies’ specification sheets. A survey was also sent out to a number of companies to elicit specifically useful information. The data for much of the newer or novel actuation schemes was obtained from research journals.

7. COMPARISON CHARTS

Six graphs have been created to compare the four basic design variables: force, displacement, frequency bandwidth, and size. Each graph is a map of where various types of actuators lie with respect to two of the variables listed above; the terms graph, map, and chart are used interchangeably. Where applicable, other parameters such as power are also indicated on the graphs.

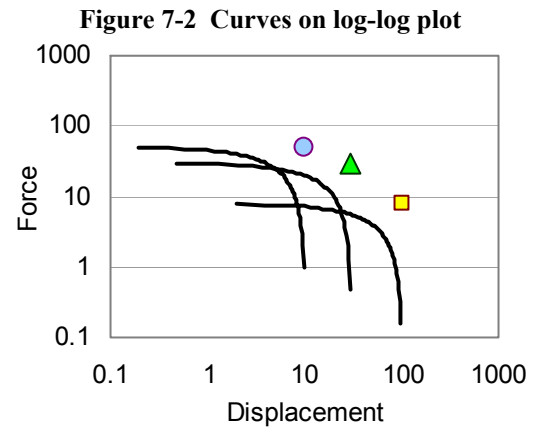
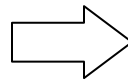
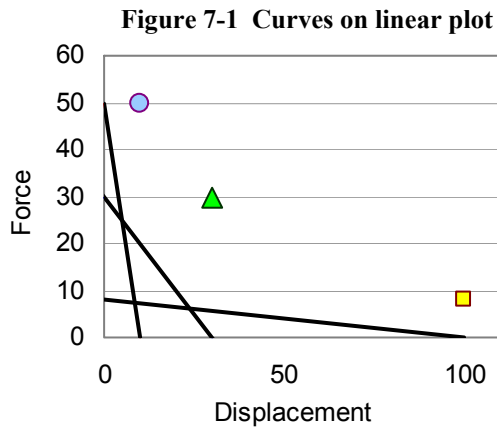
All of the graphs are log-log graphs, which enables further visual interpretation of the data. On a log-log graph, alternate axes exist $\pm 45^\circ$ to the primary axes. They represent the multiplication and division of the primary axes variables. For example, on the force versus displacement graph, an axis drawn 45° from the displacement axis represents work – the product of force and displacement.

The data for all the charts comes from the following sources:

Actuator Class	Vendors	Researchers	Books
Piezoelectrics	ACX [17] APC [18] CEDRAT [9] DSM [19] EDO [20] Ferropem [21] PI Ceramic [22] Piezo Systems [23] Sensor Tech [24] Thunder [10]	Giurgiutiu [2] Ervin [12] Janker [25] Mauck [8] Samak [26]	Janocha [27]
Magnetostrictors	AdaptaMat [28] Etrema [29]		Dorey [4] Janocha [27] Tabib-Azar [30]
Electrostrictors	Ecertec [31]	JPL's NDEAA [11] Samak [26]	Janocha [27]
SMA	Dynalloy [5] SMA-INC. [32]	AMSL [13] JPL's NDEAA [11] Chopra [33]	Janocha [27]
Electromagnetic	BSA [34] EAD Motors [35] HSI-Inc. [36] Motion Systems [37] Vickers [38]		
Hydraulic	Air Dro [39] REXA [40]		
Others	HSI-Inc. [36]		Janocha [27] Tabib-Azar [30] Osada [41]

7.1. FORCE VERSUS DISPLACEMENT

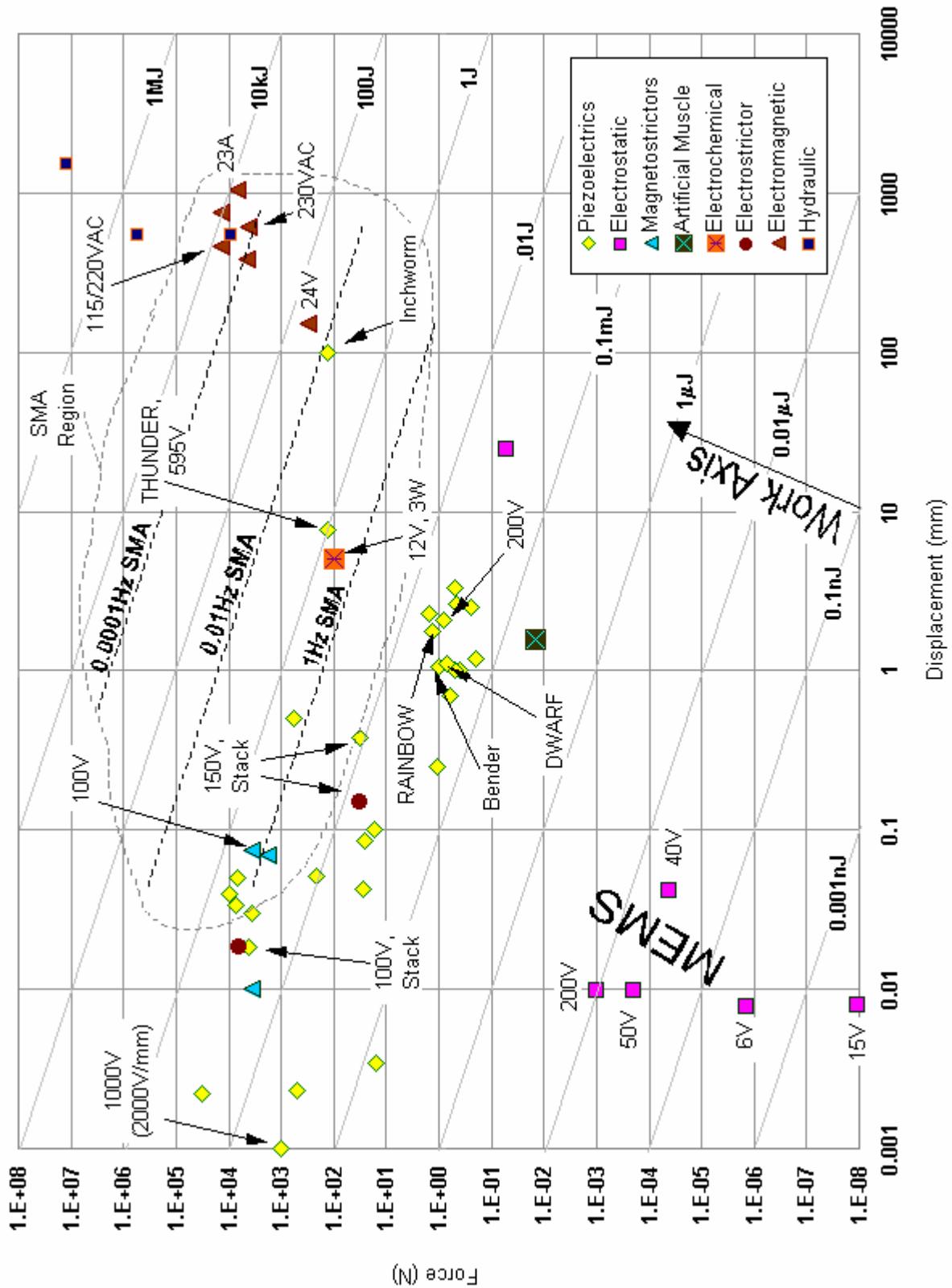
Figure 7-3 depicts the tradeoff between force and displacement. Typically, actuators with high displacement provide low force and vice versa. Even for a given actuator, the maximum force and maximum displacement are not achieved at the same time. The maximum force is the “blocking force” measured when there is zero displacement. The maximum displacement is the “free displacement” measured when there is no load in resistance. Therefore, each actuator is not represented by a point on this graph, but by a curve. The curve is linear, going from the blocking force y-intercept to the free displacement x-intercept. On the exponential plots, these lines appear as curves, as shown in Figure 7-2.



Another feature of this graph is that an axis diagonal to the two main axes represents their product, which is work. This is valuable in situations where work is the desired design variable, such as pump design.

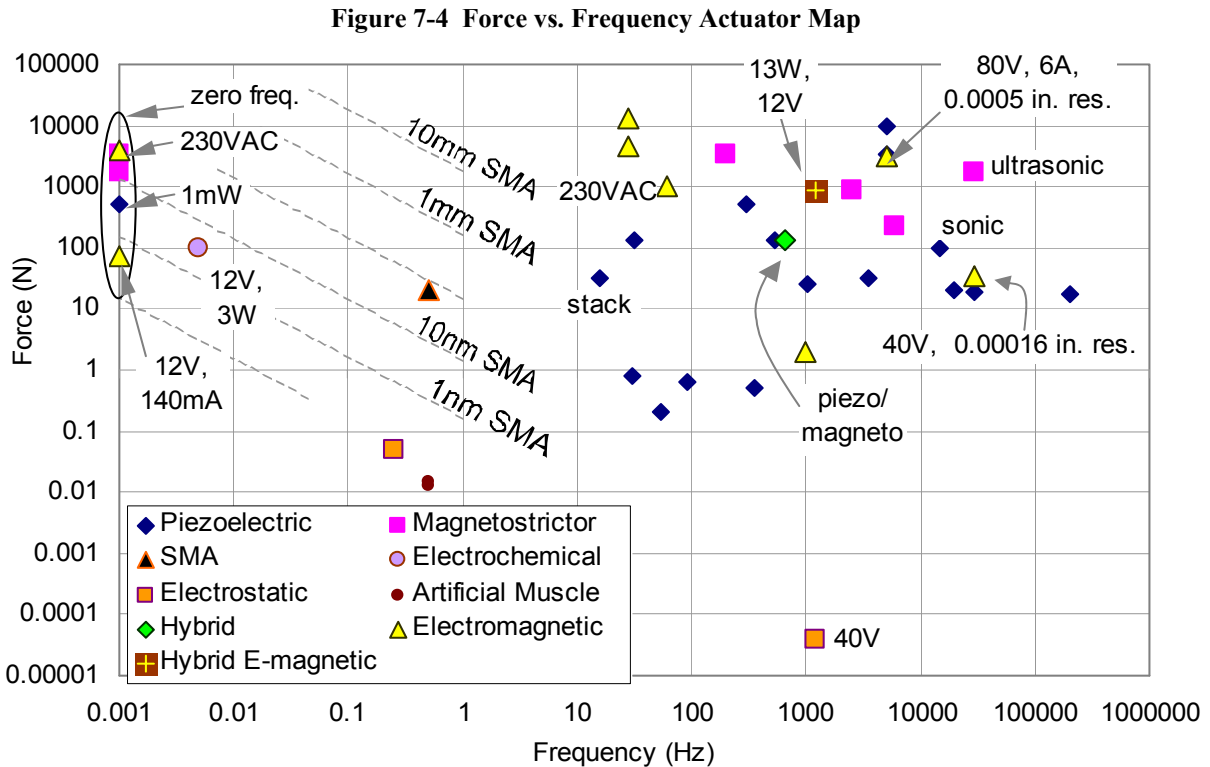
As described earlier, SMAs appear as a series of curves. Observe that the work axis corresponds with the SMA actuator curves of constant maximum frequency.

Figure 7-3 Force vs. Displacement Actuator Map



7.2. FORCE VERSUS FREQUENCY

Here we examine the design space with respect to force and frequency. It should be expected that higher force actuators are larger and would therefore have lower operating frequencies. However, this trend is not readily apparent in the sampled data, possibly due to the number of types of actuators examined.

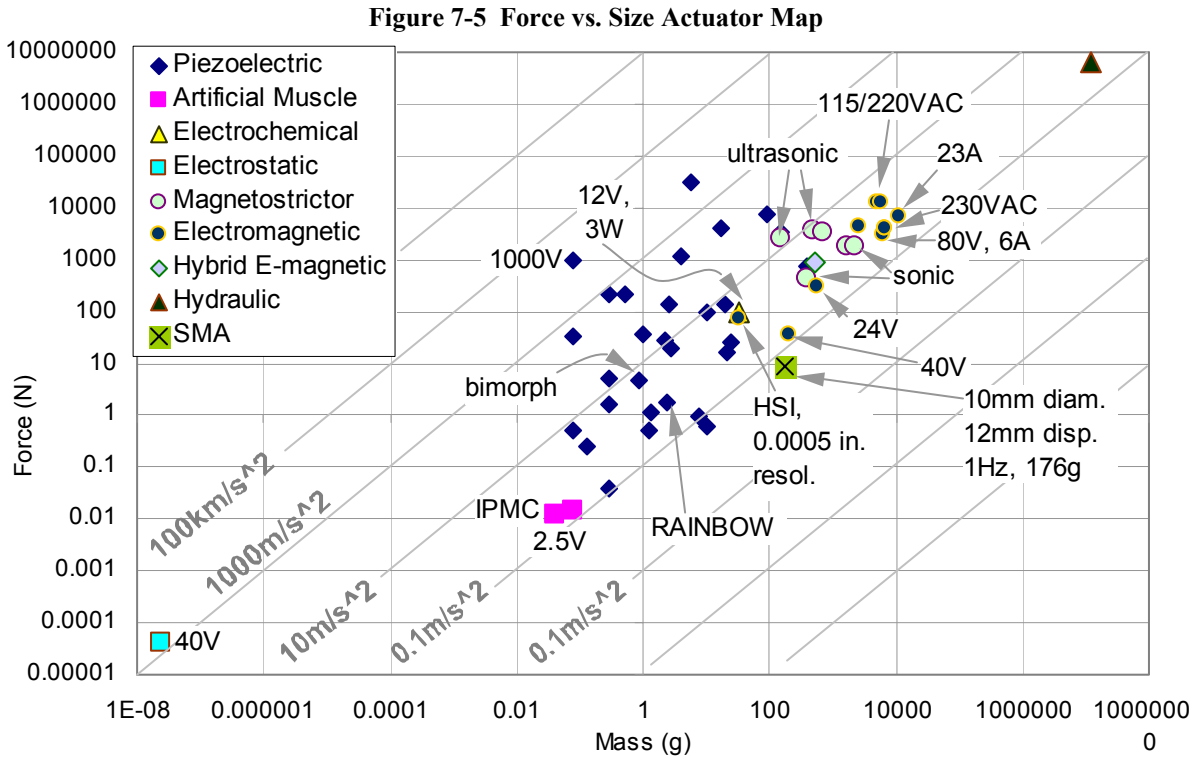


Again, note the family of SMA curves which, due to their cooling time limitations, all lie left of the 1 to 10 Hz range. Note that SMAs typically require low voltages, from 10 to 20 V.

The magnetostrictors are seen to be very high in force and also stretch across most of the frequency domain. Their disadvantage, unseen here, is their larger size and energy consumption.

7.3. FORCE VERSUS SIZE

This graph shows the design space of force with respect to size. Mass is used as the indicator of size, although volume data, which was also collected, could have been used. Here, the diagonal axis represents N/g or m/s^2 , which indicates the maximum acceleration capability for a given actuator.

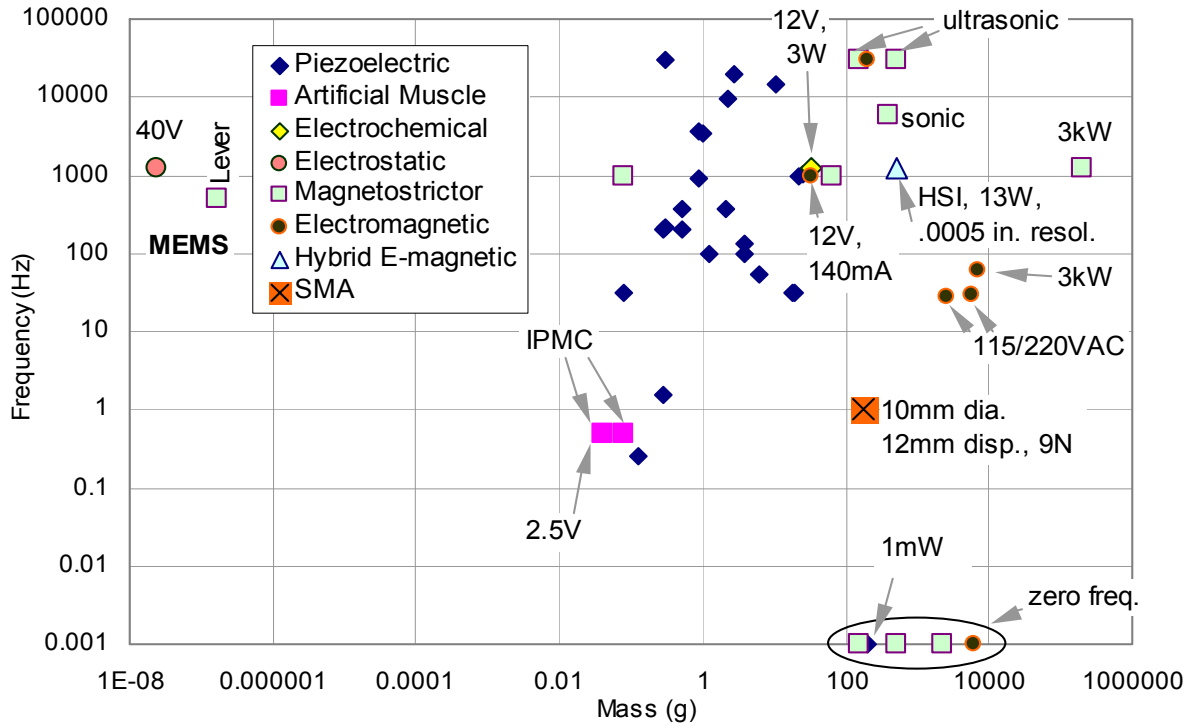


This graph provides valuable data on scaling of actuator force in different design domains. As expected, larger actuators produce greater forces.

7.4. FREQUENCY VERSUS SIZE

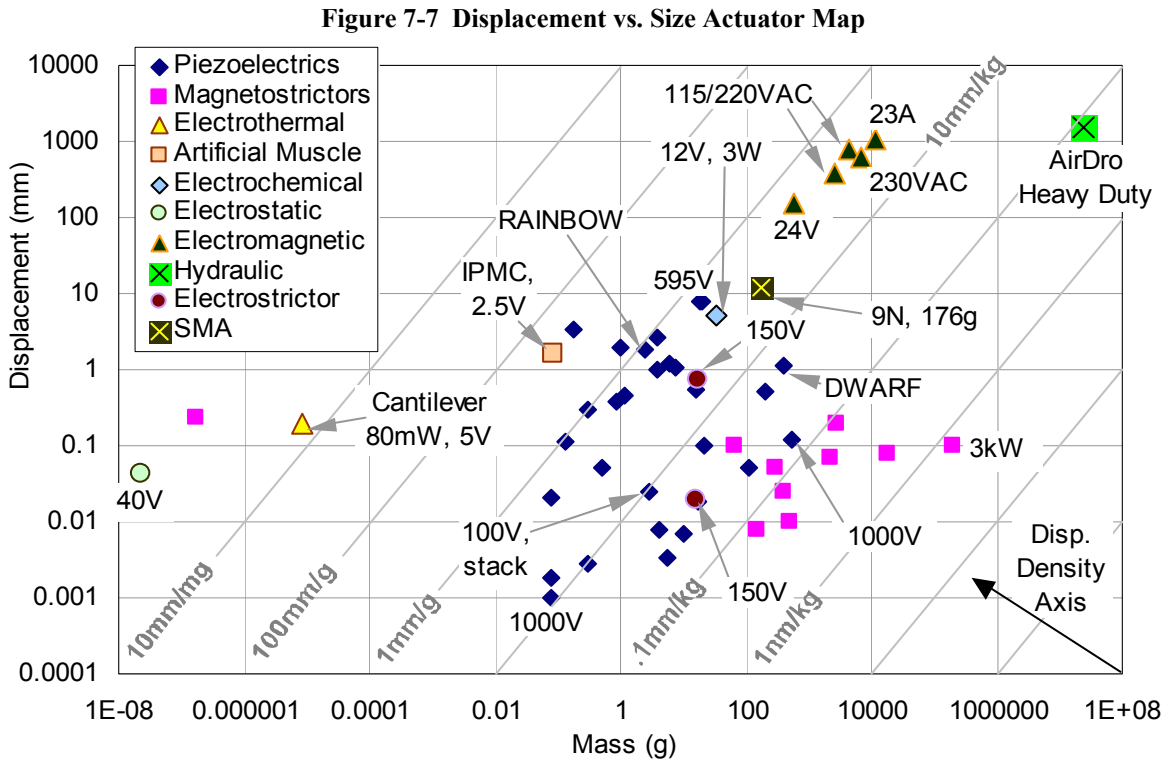
The design domain of frequency and size is seen in Figure 7-6. The formula for natural frequency, $\omega_n = \sqrt{k/m}$, predicts that smaller devices will operate at higher frequencies. However, this trend is only somewhat apparent in the sampled data. The largest of the actuators studied, magnetostrictors, are shown to operate through the same range of frequency as even piezoelectric devices.

Figure 7-6 Frequency vs. Size Actuator Map



7.5. DISPLACEMENT VERSUS SIZE

The displacement and size design space is laid out in Figure 7-7. This graph is similar to the previous graph with regards to the scaling information it contains. Smaller actuators naturally produce smaller displacements. However, note that many of the heavier magnetostrictors actually produce less displacement than the lighter piezoelectric actuators. While this is true, the magnetostrictors provide more than enough force to justify their size.

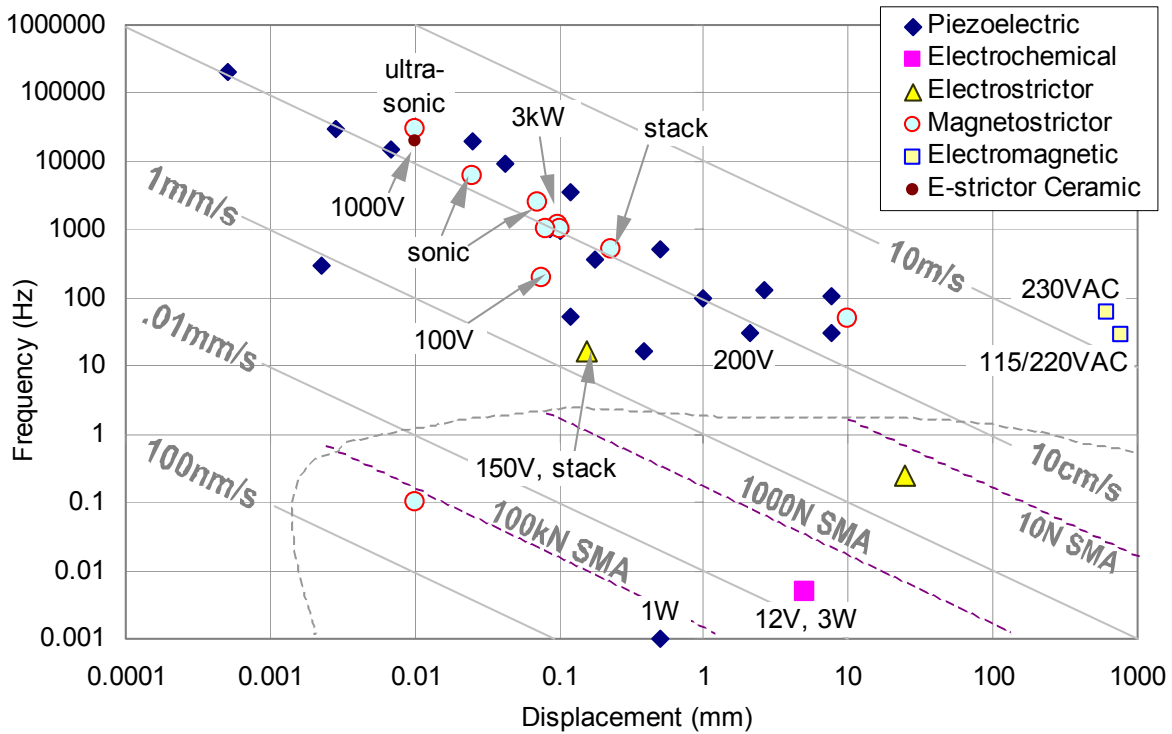


The axis of mm/g is also provided for the designer to observe the apparent “displacement density” of the various actuators.

7.6. FREQUENCY VERSUS DISPLACEMENT

The final design space examined is that of frequency and displacement, seen in Figure 7-8. As would be expected, higher displacements seem to correlate to lower frequencies, since most high-displacement devices are also larger.

Figure 7-8 Frequency vs. Displacement Actuator Map



The alternate axis derived here is Hz-m, which corresponds to speed in m/s. Note that since the Hz is cyclic, this number serves the interested designer only as a guide to the actual velocity. The speed axis also coincides with the family of SMA curves for this particular graph. Each SMA curve corresponds to a constant force. Since SMAs are limited by their power capability, moving from one force curve to another represents a change in velocity. In different words, dividing power by force gives units of velocity, which coincide with the derived velocity axis.

8. CONCLUSIONS AND FUTURE WORK

Six actuator domain maps have been created to assist designers (who are more interested in end characteristics than fundamental principles) in choosing actuators for specific applications. Most designs can be viewed as having four main requirements: force, size, displacement, and frequency. Power consumption can be treated as a cost factor for further comparison. The graphs contained in this report provide a means to find the intersections of these characteristics for given design specifications and see which actuators are available.

A difficulty in this kind of analysis and comparison is that most researchers, vendors, and designers provide abundant data in many different forms. Much of the data cannot be used to directly compare two different actuators and there are many inconsistencies from various sources. Another difficulty is that many parameters exist for one particular actuator (i.e. geometry), which greatly affects the output performances that we are measuring. This leads to ambiguities in interpretation of the graphs, which is one reason why normalized data comparisons are more typical.

The data maps contain an abundance of information, but much of it is scattered. There are few trends and the data often seems to belie common assumptions. Thus, until more data is obtained, interpretation of the graphs is limited.

In conclusion, a good framework for comparing actuators has been created. The graphs produced in this research serve well as a reference guide for the data contained within. While all the trends are not fully evident, the designer's eyes can now be opened to other possible solutions of their engineering problems.

9. RECOMMENDATIONS

Caution should be heeded by designers when interpreting actuator specifications. For example, special attention should be made to static and dynamic displacements and forces. Further, maximum free displacement and maximum blocking force are quantities that cannot exist at the same time.

In addition, the graphs contained within this report should be considered living and open to new data. Eventually, the data maps should be extended beyond two dimensions. Three dimensional actuator data curves could easily be visualized and additional dimensions could be represented by multiple curves or colors. This type of tool could portray the entire design space all at once, allowing much faster and more intuitive actuator selection.

10. BIBLIOGRAPHY

- [1] M.V. Gandhi and B.S. Thompson, Smart Materials and Structures, Chapman & Hall, 2000
- [2] V. Giurgiutiu, R. Pomirleanu, and C.A. Rogers, "Energy-Based Comparison of Solid-State Actuators", University of South Carolina Report #USC0ME-LAMSS-2000-102, 2000
- [3] Intellimat, www.intellimat.com
- [4] A.P Dorey and J.H. Moore, Advances in Actuators, IOP Publishing, 1995
- [5] Dynalloy, www.dynalloy.com
- [6] J.R. Yaeger, "A practical shape-memory electromechanical actuator," *Mechanical Engineering*, 1984
- [7] B. Clephas and H. Janocha, "New linear motor with hybrid actuator," SPIE Vol. 3021, 1997
- [8] L. Mauck, "Piezoelectric Hydraulic Pump," *Conference on Smart Structures and Integrated Systems*, SPIE Vol. 3668, March 1999
- [9] CEDRAT, www.cedrat-grenoble.fr
- [10] Face-International Corp. (Thunder), www.face-int.com/thunder
- [11] WorldWide Electroactive Polymer Actuators Webhub, ndea.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm
- [12] J. Ervin, "Design, Characterization, and Assessment of the Recurve Actuation Architecture," Ph.D. Dissertation, Univ. of Michigan, 1999
- [13] Active Materials and Structures Laboratory, amsl.mit.edu

- [14] V. Giurgiutiu and C.A. Rogers, "Power and Energy Characteristic of Solid-State Induced-Strain Actuators for Static and Dynamic Applications," *Journal of Intell Matl Sys and Struct*, September 1997
- [15] V. Giurgiutiu and C.A. Rogers, "Dynamic Power and Energy Capabilities of Commercially-Available Electro-Active Induced-Strain Actuators," *Journal of Intell Matl Sys and Struct*, November 1996
- [16] A. Moskalik and D. Brei, "Force-Deflection Behavior of Piezoelectric C-Block Actuator Arrays," *Smart Material Structures*, Vol. 8, 1999
- [17] ACX, www.acx.com
- [18] APC, www.americanpiezo.com
- [19] DSM, www.dynamic-structures.com
- [20] EDO, www.edoceramic.com
- [21] Ferroperm, www.ferroperm.com
- [22] PI Ceramic, www.piceramic.com
- [23] Piezo Systems, www.piezo.com
- [24] Sensor Tech, www.sensortech.ca
- [25] Janker, "Mechatronics Using Piezoelectric Actuators," *Journal of Euro Ceramic Society*, Vol. 19, 1999
- [26] D. Samak and I. Chopra, "Design of High Force, High Displacement Actuators for Helicopter Rotors," *Smart Material Structures*, Vol. 5, pp. 58-67, 1996
- [27] H. Janocha, *Adaptionics and Smart Structures*, Springer-Verlag, 1999
- [28] AdaptaMat, www.adaptamat.com
- [29] Etrema, www.etrema-usa.com/actuation/pdf/actuators.pdf
- [30] M. Tabib-Azar, Microactuators: Electrical, Magnetic, Thermal, Optical, Mechanical, Chemical and Smart Structures, Kluwer Academic, 1998
- [31] Ecertec, www.ecertec.com
- [32] SMA-INC., www.sma-inc.com/Actuators.html
- [33] I. Chopra, "State-of-the-Art of Smart Structures and Integrated Systems," *SPIE Smart Structures and Materials Conference*, February 1996
- [34] BSA, www.ballscrews.com/html/misc/products.html
- [35] EAD Motors, www.eadmotors.com
- [36] HSI-Inc., www.hsi-inc.com/products/actuators
- [37] Motion Systems, www.motionsystems.com
- [38] Vickers, www.vickers-systems.com
- [39] Air-Dro, www.airdro.com
- [40] REXA, www.rexa.com
- [41] Y. Osada and D.E. De Rossi (eds.), Polymer Sensors and Actuators, Springer, 2000