

Force transduction materials for human-technology interfaces

by R. Fletcher

Various approaches to sensing forces and generating forces are presented in the context of building human-technology interfaces capable of communicating force information. Addressing the need for various types of force transducers, relevant classes of materials are reviewed, including smart materials, electronic polymers, and magnetic materials. Basic physical limits and design trade-offs are given for building force sensors and actuators from these materials. In addition, the possibility of using force transduction as a means of generating electrical energy is also briefly discussed. Finally, two brief illustrative examples, "power shoes" and "deformable surfaces," are also presented.

Continuing advances in the power and complexity of electronic technology have begun to underscore the need for better interfaces between humans and technology. A key point in addressing the general problem of I/O (input/output) is to recognize that the term *interface* is not limited to the context of desktop computers, but can be applied to the general class of all electronic devices as well as active living spaces, such as automated offices or entertainment theaters. From the user's point of view, the interface is the technology, and as a result, good interfaces are essential for achieving technology that is natural and accessible to a wide range of users.

Our sense of touch is a primary means of interaction with our environment, and for this reason, it is desirable to create interfaces between humans and technology that feel natural and include the entire set of sensory interactions—sight, sound, taste, smell, and touch. If we set out to create interfaces that can communicate force information, a wide range of sizes is

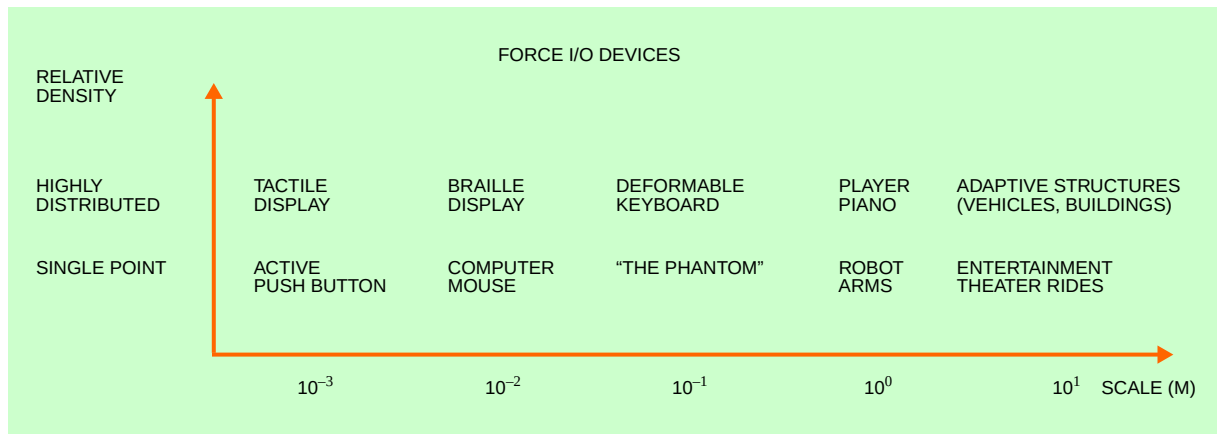
conceivable, capable of sensing and generating time-varying forces either at a single point or on a distributed array of points (e.g., a surface). This range of possibilities is represented graphically in Figure 1.

On a relatively small scale, a single-point force transducer can be as simple as a push button that senses or generates fingertip forces, whereas on a larger scale, for example, a single-point force transducer could be a chair in a virtual reality ride that can measure a person's weight and can move or vibrate under software control. Distributed-force I/O devices, in contrast, are perhaps best described as active surfaces, which can sense or generate distributed forces, or do both. On the millimeter size scale, for example, one such "distributed-force display" would be capable of reproducing fine fabric textures that could be felt with a fingertip, whereas a meter-size force display would be capable of reproducing a large three-dimensional (3D) topographical terrain map that could be felt with two hands.

At present, the force or tactile interaction found in electronic technology is poorly developed, and progress in the general field of haptic interfaces has been slow.¹ The extent of our touch interaction with electronic appliances is generally limited to pushing some sort of key or button with a finger. Present con-

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Figure 1 Range of possible interfaces



sumer electronic devices do not sense how hard a button is pushed, cannot measure the size of the contact area, and have no real means of communicating any tactile or force information back to the user. Research in academia² and industry³ has produced a variety of technical solutions employing either clever mechanical structures or electromagnetic force fields. Perhaps the most well known of recent inventions is "The Phantom,"⁴ a general-purpose single-point haptic interface that allows the user to feel virtual 3D objects using a single finger. Although these technologies represent significant advances in the development of force I/O devices, research in applying force transduction devices to computer interfaces is still in its infancy.

In addition to clever mechanical design, continuing advances in material science have begun to provide opportunities for innovative force I/O devices. In many applications, novel materials may offer simpler or cheaper approaches to force sensing and actuation. In order to create future consumer technology that can measure contact pressure or contact area and can temporally reproduce a variety of surface shapes or textures with good spatial resolution, it is certainly desirable to develop practical affordable force sensors and actuators. It is with this motivation that a review of relevant force transduction materials is presented.

Approaches to force transduction

The ability of electronic appliances to sense or to generate forces requires that electrical energy be con-

verted to mechanical force—and vice versa—via some sort of transduction mechanism. Although there exist a wide variety of physical mechanisms that can be used to sense or generate forces, it is desirable within the context of electronic appliances to focus on force sensors and actuators that employ electronic mechanisms such as voltages, currents, or electromagnetic fields. In addition, it is desirable to create sensors and actuators that are mechanically simple and robust, and that can be used as building blocks to create force I/O devices.

Classic examples of electromechanical force transducers, such as a solenoid plunger or movable plate capacitor, have existed for over one hundred years. Although electrostatic systems have been demonstrated in the form of micromachined motors⁵ or force actuators,⁶ the use of such devices in electronic appliances or computer peripherals has been generally limited by device size, manufacturing cost, output force or displacement, and power requirements. Recent advances in materials technology, however, have renewed interest in electromechanical structures and have created the potential for new types of electromechanical force transducers based on interesting materials instead of clever devices. Three general overlapping classes of materials that are particularly attractive for such applications are: smart materials, polymers, and magnetic materials. These types of material will be described briefly.

Smart materials. Perhaps the most significant technological development in force transduction is the dis-

covery of various “smart” materials, which are materials that exhibit interesting behavior in response to external stimuli. In particular, piezo or strictor materials are naturally suited for force transduction since they undergo strain deformation in response to certain external stimuli such as an electric field, magnetic field, or temperature change. The inherent electromechanical response of such materials thus allows a single piece of material to replace a more complicated electromechanical device previously needed to perform the same function. For example, a piezoelectric crystal can be used in place of a capacitor device to

**Smart materials exhibit
electromechanical responses
bidirectionally, accepting and
producing force.**

measure an applied force by sensing the generated voltage. In addition, the electromechanical response of these materials is generally bidirectional, so the same piezoelectric crystal can also be used to generate force by applying a voltage. This built-in functionality of smart materials enables the construction of force transducers that are simpler and cheaper than those of previous technology. At present, the materials most attractive for electromechanical force transduction are piezoceramics, piezopolymers, magnetostrictive materials, and shape-memory alloys; each of these materials is briefly described below.

Piezoceramics. Discovered in 1880 by Jacques and Pierre Curie, piezoceramics are probably the best developed and best understood of all smart materials. An electric field applied to the piezoceramic produces an elastic strain, which in turn can provide an external force. The functional dependence of the strain on the applied field is predominantly linear in piezoelectric materials but can also be nonlinear, as observed in electrostrictor materials such as PMN (lead manganese niobate).⁷ Since an applied force also produces a measurable polarization in piezoelectric ceramics, these materials can also be used as force sensors; but their

most popular uses have generally been as force actuators and oscillators in electronic watches or tuning devices.⁸ Because the strain produced by a single ceramic element is rather small (typically <0.01 percent for PZT, lead zirconate titanate), however, displacements on the order of 0.1 millimeter or greater can be achieved only by stacking together many ceramic actuator elements.⁹

Piezopolymers. Several synthetic polymers, particularly polyvinylidene fluoride (PVDF), also exhibit piezoelectric properties.¹⁰ Although existing piezopolymers generally lack the stiffness required for most actuator applications, their flexibility and manufacturability has made them popular for use as thin-film contact sensors and acoustic transducers.¹¹

Magnetostrictors. Certain ferromagnetic materials undergo elastic strains when subjected to an external magnetic field.¹² At present, the compound $Tb_3Dy_7Fe_2$, known as Terfenol-D, exhibits the largest magnetostriction, producing strains up to a few tenths of 1 percent.¹³ Although such strains are larger than those achievable in piezoceramic materials, optimum performance requires that a stress be applied to the magnetostrictor prior to actuation, which renders certain applications impractical. Another class of interesting magnetoelastic materials is amorphous iron alloys, known as metallic glasses. Cut in the form of small strips, metallic glasses are commonly used as resonating elements for shoplifting tags¹⁴ or as tensile force sensors.¹⁵

Shape-memory materials. Certain metal alloys, known as shape-memory alloys (SMAs), exhibit shape-changing phase transformations when subjected to changes in temperature. In certain alloys of NiTi, the austenite to martensite phase transformation has been used to fabricate wire or springs that actively deform when heated above a certain activation temperature.¹⁶ Heat can be applied to the metal elements either externally or by applying an electric current directly to the elements. Shape-memory metals are capable of producing large actuation strains (approximately 8 percent), although for dynamic applications, the cycle times are severely limited by thermal time constants. However, if the metal is used in the form of thin wires, the cycle times can be improved dramatically through the use of current pulses, proper pretreatment of the alloy, and carefully designed control algorithms.¹⁷ Shape-memory ceramic materials (e.g., PLZT, lanthanum-doped lead zirconate titanate), which can be activated by an electric field instead of heat, have also

Table 1 Comparison of active materials

	PZT5H	PMN	PLZT	PVDF	Terfinol-D	SMA (NiTi)	Conducting Polymer	Polymer Hydro-gel	Human Muscle
Max strain ($\times 10^{-6}$)	300	600	3000	200	1800	70000	20000	400000	400000
Max stress (MPa)	19	72	180	~1	90	190	180	0.3	0.3
Density (kg/m ³)	7500	7500	~7500	1780	9250	6450	~1500	~1300	1037
Modulus (GPa)	62	120	~60	3	40	78	5	<0.1	.06
Efficiency (%)	56	75	?	2	40	>3	>30	30	>35
Bandwidth (Hz)	1000	1000	?	1000	100	3	>1	.1	4
Energy density (KJ/m ³)	2.9	22	?	~1	19	>10	>1	0.4	0.8

been discovered but are still in the developmental stage.¹⁸

Piezoresistive polymers and polymer composites.

Another promising class of materials for force transduction consists of electronic polymer materials. The field of polymer science continues to advance tremendously, and there now exist various types of polymers that behave to some degree like the more common metal- or ceramic-based smart materials.¹⁹ However, since most smart polymers are still in early development, an alternate approach has been to use polymers for sensing or measuring force indirectly. These materials are grouped separately from smart materials because the mechanism employed is not reciprocal (e.g., applying an electrical stimulus will not produce a force output). Rather than performing force transduction through direct conversion of mechanical energy to electrical energy, as in PVDF, certain types of polymers can be used to modulate an electric current via a force-dependent electrical resistance. Polymer sensors can be used in compression as well as extension and can function over a greater range of strains than conventional metal strain gauges.²⁰

The two most common physical mechanisms employed in resistive polymer force sensors are piezoresistance and geometric deformation. The deformation type of force sensor is comprised of a conducting polymer strip or foam (such as polypyrrole) and relies simply on the deformation of the polymer to vary the conducting cross section, thus changing the resistance. Piezoresistive sensors, in contrast, generally consist of a semi-insulating polymer matrix contain-

ing some type of conducting particulates, such as graphite. Such compounds are macroscopically piezoresistive but also exhibit noise and hysteresis due to the percolative nature of the conduction mechanism. Although some mildly piezoresistive polymers have been synthesized, practical force sensors comprised of a homogeneous piezoresistive polymer are not yet commercially available.

Rare-earth permanent magnets. The discovery of new rare-earth magnetic materials, such as NdFeB, has led to the development of compact electromagnetic actuators, which represent perhaps the most attractive technology for force actuators requiring large displacements, as a possible substitute for hydraulic actuators.²¹ Using a geometry similar to that of solenoid actuators, linear electromagnetic actuators made from permanent magnets can produce forces as high as 2000 foot-pounds over a 24-inch stroke. Cleaner and less noisy than hydraulic actuators, compact powerful permanent magnets driven by magnetic fields may also be employed as large-displacement dynamic elements to transmit sound or vibration.

Other materials. Some of the materials mentioned in this paper will most likely be superseded by new classes of force transduction materials that are currently being synthesized or are yet to be discovered. In some cases, new process technologies will enable new materials to be processed, such as the powder metallurgy and rapid solidification process that enabled the fabrication of amorphous metals. In other cases, the advent of powerful computers and the increasing ability to engineer materials on the molec-

ular level will guide the discovery of other new materials.

For the near-term future, however, polymer materials appear most promising for creating new types of force transduction materials. At present, the development of contractile polymer hydro-gels²² continues to be an active area of research, and the discovery of electrically activated solid conducting polymers²³ appears to hold the greatest promise for use as versatile actuators.

Discussion

Trade-offs. Force transducer design is a game of trade-offs. Although it is convenient to compare various types of smart materials, each type of material has unique advantages and disadvantages that may be relevant to a particular application. Some of these properties are summarized in Table 1. Since the electrical and mechanical properties of smart materials are so strongly coupled, it is a common challenge to fully characterize and model all relevant electromagnetic and mechanical parameters over the full range of operational conditions.

For certain applications, we also need to keep in mind that a smart material may not always be the best answer. Although smart materials are particularly useful for actuation and sensing of dynamic forces, static forces do not supply a continuous source of energy. Therefore, the best approach to sensing static forces may be via an indirect means by constructing a simple device such as a squeezable capacitor. Such devices can be fabricated photolithographically to make microsensors on a silicon chip as employed in MEMS (microelectromechanical systems) technology.²⁴ With the increasing capability in the field of photonics, small fiber optic devices that can measure displacement interferometrically are now also possible.²⁵

Geometric alternatives, such as choosing between a sensor array versus a fixed-point sensor, present another practical consideration to sensing. For an array, the density of sensors certainly depends on the particular physical mechanism of the sensing material. For example, because of the prestress requirement, and because coils are usually required to generate magnetic fields, magnetostrictor actuators are generally physically more cumbersome to construct than piezoceramic actuators. Therefore, for array applications with high fill factors, piezoceramics

or piezopolymers would be preferred.

In addition to the physical constraints, the proper design of a force transducer must address the coupling between the electromagnetic and mechanical (or thermal or both) properties of the system. For example, the coupled constitutive relations for a piezoelectric material are given by

$$\begin{aligned} D &= e_T E + dT \\ S &= dE + s^E T \end{aligned}$$

where E is the electric field, D is the electrical displacement, S is the mechanical strain, T is the mechanical stress, d is the piezoelectric coefficient, e_T is the complex permittivity at zero stress, and s^E is the mechanical compliance at zero field. E , D , S , and T are all second-order tensors.

Similarly, the constitutive relations for a magnetostrictive system are given by

$$\begin{aligned} S &= s^H T + dH \\ B &= dT + m^T H \end{aligned}$$

where H is the applied magnetic field, B is the magnetic flux density, S is the mechanical strain, T is the mechanical stress, d is the magnetostrictive coupling coefficient, m^T is the complex permeability at constant stress, and s^H is the complex mechanical compliance at a constant magnetic field.

Once the proper form of the coupled equations that are appropriate to the applied boundary conditions are chosen, the principle of virtual work based on Hamilton's Principle can be applied to produce two coupled dynamic equations. One of the resulting equations of motion relates the *applied* forces to the electromagnetic variables and is called the sensor equation, and the other relates the *output* forces to the electromagnetic variables and is called the actuator equation. For nontrivial geometries, the equations describing the behavior of the system are usually solved numerically, often using finite-element techniques.

In order to optimize force transducer and sensor design, a better theoretical understanding of force transduction and relevant materials is certainly valuable. Fortunately, the advent of smart materials has given rise to a variety of theoretical analysis techniques that are applicable to all types of electromechanical systems and to force transduction in general.

Although modeling nonlinear actuators and exact calculation of the energy efficiency and loss mechanisms in such systems is still an active area of research, a general theoretical framework²⁶ now exists to describe the dynamic behavior of various classes of electromechanically coupled structures.

Physical limits. In considering the realm of possibilities for force transduction devices, it is useful to keep in mind the relevant physical limits for sensing and actuation.

Sensing. The limit of the smallest force that can be sensed depends on the sensing mechanism involved. The technical and commercial success of Atomic Force Microscopy and related scanning probe technologies²⁷ demonstrate that there are certainly clever ways to sense even atomic-scale forces. The simplest example of a sensitive force measurement is perhaps a resonant circuit employing a parallel-plate capacitor with a squeezable dielectric: As a force is applied on the capacitor plate, the capacitance changes, producing a shift in the resonant frequency that can be measured with very high precision. Clearly, good mechanism design is a crucial aspect of accurate force transduction.

However, without resorting to clever devices, an issue that is more salient to force transduction materials is to consider the response of the intrinsic material itself. In the case of a smart material, such as a piezoelectric or magnetostrictive material, an applied force will produce a change in some measurable electrical property of the material. The magnitude of the electromagnetic response generally depends on the amount of strain produced from the applied stress and how the magnitude of the response depends on this strain. Generally, the material modulus determines the amount of strain, and the electromagnetic coupling coefficient determines how much the electronic properties change in response to a given strain. Maximum sensitivity would thus be achieved by choosing a material with a low modulus but with a high coupling coefficient. As seen in Table 1, no material presently has such properties. For those applications that can tolerate low mechanical stiffness, PVDF is generally chosen over a piezoceramic material because of its low modulus and relatively low cost, despite its relatively low electromechanical coupling coefficient. Since metals and ceramics have relatively large moduli, perhaps the optimal force-sensing material in the near future will be some type of polymer with a high coupling coefficient. For measuring static forces, via

either a piezoresistive or a capacitance mechanism, the limit of sensitivity will naturally depend on the resistive and dielectric properties of the material, while minimizing any hysteretic effects or noise due to internal inhomogeneities or anisotropies.

The limit of the smallest force that can be sensed depends on the sensing mechanism involved.

Actuation. The maximum force exerted by any material is necessarily limited by its maximum stress. If the actuation results in a compressive stress (a “pushing” force) this naturally sets a lower limit on the required stiffness of the material. In order to maximize the actuation force, it is generally desirable to employ a material with a large maximum stress capable of large actuation strains. However, since very high-stiffness materials generally produce small strains and can even be brittle (low maximum compressive or tensile stress), it seems unlikely that both parameters can be optimized in the same materials. As a result, the maximum actuation force of future materials may not be vastly greater than the forces achievable at present.

For actuator devices made from rare-earth permanent magnets, the relevant material property limiting the actuation force is the remnant magnetization, B_r . It can be shown that the force output is directly proportional to B_r , depending on the design of the actuator. If we take a physical limit for NdFeB in the saturation magnetization of its elements, this gives a BH product of approximately 150×10^6 or $B_r = 16$ kilogauss (kG), if we assume a coercivity H_C of approximately $B_r/2$. This value is approximately three times greater than the values presently achievable. Therefore, neglecting any major improvement in actuator design, it can be reasonably expected that the force output of

future magnet-based actuators may be improved by a factor of three, but probably not by much more.²⁸ Nonetheless, this amount of improvement is sufficient for a wide variety of applications.

Given the trade-off between stiffness and strain, perhaps the more interesting physical limit to consider is the maximum actuation strain that is achievable by a material. Emulating the function of muscle groups in biological organisms, low-stiffness materials with large actuation strains can provide an effective source of tensile actuation (“pulling force”). Although the various mechanisms that produce strain take place on a microscopic scale, certain mechanisms such as the phase transitions of shape-memory alloys can produce relatively large strains approaching 10 percent, limited mainly by the yield strength of the metal. However, in the case of polymer gels, the ability of long molecular chains to reorient themselves in response to electrochemical stimuli can produce very dramatic macroscopic contractile strains of 1000 percent or more, which is basically a function of the molecular geometry and local electronic structure.²⁹ If such active polymers prove to be practical, it may suggest future approaches to force actuation based on molecular motors.

Applications

Force transduction materials are generally discussed in the context of adaptive structures, where a typical application may be to actively cancel unwanted mechanical vibration such as acoustic noise.³⁰ An exciting but relatively unexplored range of applications, however, is to extend the use of this technology to generate electric power or to create new classes of conformable sensors and deformable surfaces for electronic appliances. With this in mind, we proceed to describe two simple illustrative examples that employ force transduction mechanisms to generate electrical energy and to generate force or acoustic energy.

Power shoes. The ability to convert mechanical energy into electrical energy naturally leads to the idea of creating new devices that can generate electric power from force. Since the conversion efficiency of the transduction mechanism may not be high, such devices should not be viewed as an efficient means of generating power, but rather as a means of recovering a certain amount of available mechanical energy that is normally lost through dissipative processes. This means of generating power would be of particular

interest under circumstances where other sources of energy such as batteries or solar energy are not available.

An interesting application of this technology would be to recover some of the energy dissipated during walking or running through the use of force transduction in our shoes.³¹ The relatively large volume of material in shoe soles and heels is adequate for embedding piezoelectric materials and electronic components into our shoes. If a practical means can be found to store the charge produced by the piezoelectric material, the resulting voltage can be used to run various low-power electronic components. New forms of personal communication and data storage devices that could be powered via this means is an area of ongoing research at the MIT Media Laboratory.³²

Deformable surfaces. Aside from generating electric power, another class of applications for force transduction materials consists of deformable surfaces. A desktop version of such a distributed-force actuator array could be used as a quasi-3D display device. With such a device, one could imagine, for example, being able to download 3D objects from the World Wide Web and reproducing the surface of the Rosetta Stone or prehistoric fossils. Since such a display could also be made touch-sensitive, a deformable surface could also be used as a universal force I/O panel. The front panel on any type of electronic appliance could thus be made software-reconfigurable so that the appropriate push buttons or keys would pop out as needed. A flat writing tablet could then be transformed at will into a keyboard with any arbitrary number of keys. Conceivably, if the usable frequency response (bandwidth) of a deformable surface extends to 20 kilohertz (kHz) or so, it could be used to transmit and receive sound as well.

The basic technical requirements of deformable surfaces are spatial resolution, actuation speed (bandwidth), and displacement—all of which are limited with existing technology. An additional implicit requirement for consumer electronic appliances is reasonable cost. At present, perhaps the closest approximation to deformable surfaces are Braille displays, such as those made with piezoelectric actuators;³³ however, these displays are relatively costly and lack the displacements required (> 1 centimeter would be nice) for general-purpose use. It is unclear at this time whether future deformable surfaces will be made from super-large arrays of microactuators or

made from sheets and strips of controllably deformable smart materials.

Summary

Electronic technology need not be concentrated in a television set or stereo system or in a computer box that can crunch numbers and process words. Advanced sensors and interfaces will enable electronic technology and computation to be distributed throughout our environment. Although the idea of power shoes and deformable surfaces might seem unrealistic at present, this technology is brand new, and it is perhaps not imprudent to consider new applications of force transduction devices to a wide range of consumer products and electronic devices. Materials technology now allows sensors and actuators to be embedded into the everyday objects around us—into chairs, tables, walls, shoes, coffee mugs, and even our clothing. Force transduction materials allow the creation of intelligent physical objects that can feel and can be felt, as well as objects that can move or generate power. Such technology also enables a new class of computer peripherals in the form of tactile objects that can be used to manipulate or display complex data objects.

Since touching and feeling are fundamental interactions between humans and their environment, force transduction will be an essential element of future user-friendly environments. In addition to generating force or movement, the increasing need for portable and wireless electronics will require new materials and mechanisms to generate and store energy. Although smart materials, electronic polymers, and rare-earth magnets offer interesting opportunities for creating new force-related devices, the design of such devices involves many trade-offs between various material properties and device requirements. The market for force transduction devices is still in its infancy, but it is certain that materials science will continue to play an important role in this emerging technology.

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