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Piezoelectric actuators 2006

Expansion from IT/robotics to ecological/energy applications

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Abstract Piezoelectric actuators have been commercialized in various areas such as information technology, robotics, bio-, medical engineering, ecological and energy engineering. This paper reviews their recent application developments and foresees the future of piezoelectric actuators.

Keywords Piezoelectric Actuators · Ultrasonic motors · IT · Robotics · Biomedical application · Energy harvesting · Ecological application

1 Introduction

The first mass-production industrial application of the piezoelectric actuators must be a dot-matrix printer by NEC [1], which was motivated by the invention of the co-fired multilayer actuator (MLA) by The Penn State University [2]. In the following a couple of years, camera applications such as shutter with a bimorph by Minolta [3] and auto focus mechanism with an ultrasonic motor by Canon [4] were widely commercialized. In parallel, the piezoelectric linear actuators were utilized for precise *x–y* stages in late 1980s owing to the demand by semiconductor manufacturers [5]. Automobile application of the MLA started after getting into 1990s; Toyota introduced the MLA to the damper, which is electronic modulated suspension [6]. Siemens succeeded to use the MLA even in a considerably severe high temperature condition for the diesel injection valve control [7]. Some of the important developments in the key technology and their commercialization are summarized in Table 1 [8].

In general, taking into account the difficulty in overcoming the reliability requirements such as operating temperature range and lifetime, we engineers recognize the development "pecking order" in the sequence like "Camera" > "Office equipment" > "automobile" [9]. Since the MLA has been already utilized for the diesel injection valve, we could say that "the piezoelectric actuator development has already gotten into a maturing period." Further, we can say that "the industrial competition has started in sharing the market by reducing the actuator price drastically," which is not only related with the technological development, but also with the industrial managerial decision.

This paper reviews the recent developments of piezoelectric actuators, transformers and ultrasonic motors, and foresees the future of them. We will consider the developments from the "need-pull" (rather than "seed-push") viewpoint; that is, information technology, robotics, bio- and medical engineering, ecological and energy engineering. The topics covered in this article are illustrated in Fig. 1.

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2 Why piezoelectrics?

The advantages of piezoelectric devices over electromagnetic (EM) types are summarized [10]:

a. More suitable to miniaturization—

From the market research result for 80 Japanese component industries in 1992, tiny motors in the range of

Table 1 Development history in piezoelectric actuators.

Year	Key technology	Commercialization
1978	PMN electrostrictor (Penn State)	
1978	Cofired MLA (Penn State)	
1981	High d/k single crystal (TI Tech)	
1982	Ultrasonic Motors (Shinsei)	
1987		Dot matrix printer (NEC)
1987		Camera auto focus (Canon)
1988	Linear π-type USM (Shophia U)	
1989		Camera shutter (Minolta)
1989	Monie/Cymbal (Penn State)	Piezo suspension (Toyota)
1990		Headrest control (Toyota)
1995		Inkjet printer (Epson)
1999		Wrist watch (Seiko)
2000		Diesel injection (Siemens)
2000	Compact USM (Penn State)	

5–8 mm are highly required for the office and factory automation equipment. But the conventional EM motors are rather difficult to produce with sufficient energy efficiency. Since the stored energy density of the piezo-device is larger than that of an EM type, 1/10 smaller in volume and weight can be achieved for micro motors.

b. No electromagnetic noise generation—

Since magnetic shielding is not necessary, we can keep a compact design.

c. Higher efficiency—

Figure 2 shows efficiency versus power relation for electromagnetic and piezoelectric devices [We collected 3000 data from the commercial EM motor catalogs (2000)]. The significant decrease in the efficiency of the EM motor is mainly due to the Joule heat increase in reducing the coil wire thickness. More than 95% of the input electrical

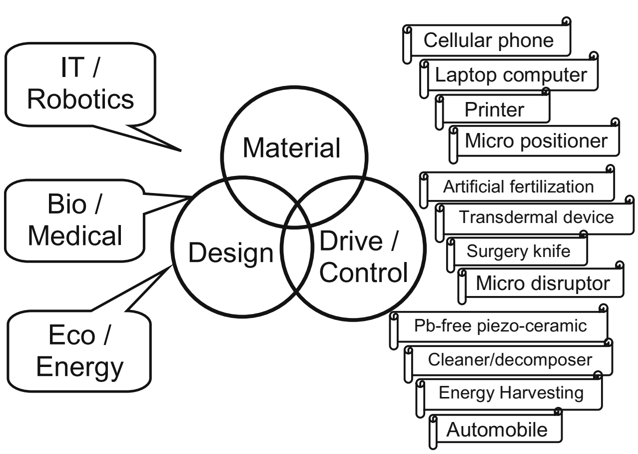


Fig. 1 Piezoelectric actuator developments are motivated typically by three areas: IT, Bio and Eco engineering

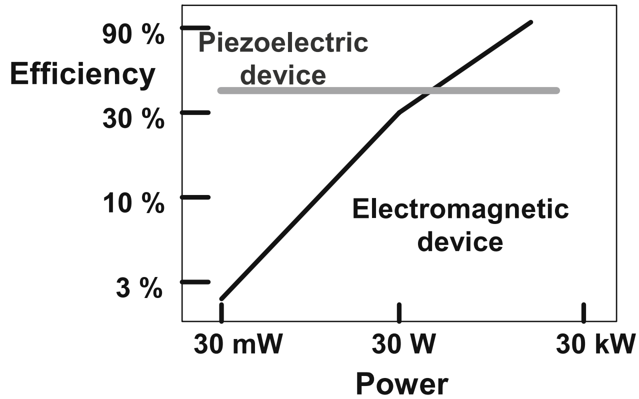


Fig. 2 Efficiency vs. power relation for electromagnetic and piezoelectric devices

energy in a wrist watch motor is spent to generate heat! Since the efficiency of the piezo-device is insensitive to the size, it is effective in the power range lower than 30 W.

d. Non-flammable—

Moreover, the piezo-device is safer for the overload or the short-circuit at the output terminal.

3 Information tech applications

Cellular phone applications are the current major focus of the piezo-actuators. Laptop computer applications of a piezoelectric transformer and a piezo-pump are also moving quickly, while the conventional piezoelectric inkjet printer became minimum inexpensive nowadays owing to the simplest manufacturing process. Optical communication applications are still behind with wide commercialization.

3.1 Cellular phone

Eighty percent of the present cellular phones installed a camera already, among which the newest versions from the beginning of 2006 have an automatic focus mechanism. The next target of the manufacturers will be an optical zoom (i.e., by mechanical motion, not "digital" zooming) mechanism by the end of 2007. The auto focus requires only 0.2 mm motion of the lens, which can be satisfied by a sort of bimorph, such as a "Helimorph" [11]. However, the optical zoom requires more than 2 mm stroke, which can be realized either a micro ultrasonic motor (USM) or an impulse motor.

In collaboration with Samsung Electromechanics, Korea, The Penn State University developed a zoom mechanism with two micro rotary motors [12–14]. A micro motor called "metal tube type" consisting of a metal hollow cylinder and two PZT rectangular plates was used as basic

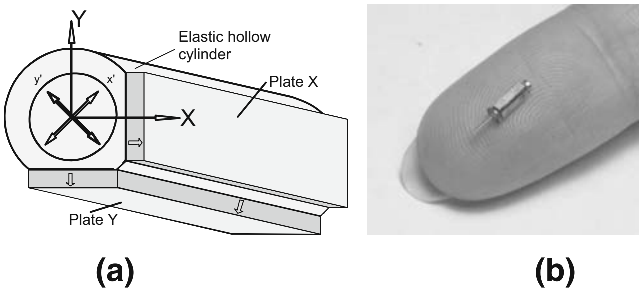


Fig. 3 "Metal tube" motor using a metal tube and two rectangular PZT plates. (**a**) Schematic structure, and (**b**) photo of a world-smallest motor (1.5 mmϕ).[12,13]

micro actuators [See Fig. 3(a)]. When we drive one of the PZT plates, Plate X, a bending vibration is excited basically along x axis. However, because of an asymmetrical mass (Plate Y), another hybridized bending mode is excited with some phase lag along *y*-axis, leading to an elliptical locus in a clockwise direction, like a *Hula-Hoop* motion. The rotor of this motor is a cylindrical rod with a pair of stainless ferrule pressed with a spring. The assembly is shown in Fig. 3(b). The metal cylinder motor 2.4 mm in diameter and 12 mm in length was driven at 62.1 kHz in both rotation directions. A no-load speed of 1,800 rpm and an output torque up to 1.8 mN·m were obtained for rotation in both directions under an applied rms voltage of 80 V. Rather high maximum efficiency of about 28% for this small motor is a noteworthy feature.

The world-smallest camera with both optical zooming and auto focusing mechanism for a cellular phone application developed in 2003 is shown in Fig. 4. Two micro ultrasonic motors with 2.4-mm diameter and 14-mm length were installed to control zooming and focusing lenses independently in conjunction with screw mechanisms.

A competitive technology is an impulse motor. Konika–Minolta developed a Smooth Impact Drive Mechanism (SIDM) using a ML piezo-element [15]. The idea comes from the "*stick & slick*" condition of the ring object attached on a drive rod in Fig. 5. By applying a saw shape voltage to a multilayer actuator, alternating slow expansion and quick shrinkage are excited on a drive friction rod (see Fig. 6). A ring slider placed on the drive rod will stick on the rod due to friction during a slow expansion period, while it will slide during a quick shrinkage period, so that the slider moves from the bottom to the top. A lens is attached to this slider. In order to obtain the opposite motion, the voltage saw shape is reversed. Compared to the USMs, the impulse motor is simpler, but the 1/10 smaller holding force may be a problem.

Fig. 4 Camera auto zooming/focusing mechanism with two metal tube USM's in a Samsung cellular phone.[14]

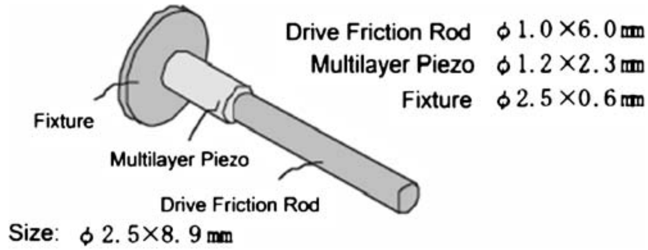


Fig. 5 Illustration of the SIDM.[15]

3.2 Laptop computer

NEC recently news-released their piezoelectric pump water cooling module for a fuel cell power supply in a laptop computer (Fig. 7).

Recent lap-top computers with a liquid crystal display require a very thin, no electromagnetic-noise transformer with a high efficiency as an inverter of a fluorescent backlight. This application has accelerated the development of the piezo-transformer. The piezo-transformer has input and output terminals fabricated on a piezo-device, and the input/output voltage is changed through the vibration energy transfer. NEC recently commercialized a multilayer rectangular type transformer in order to increase the voltage step-up ratio, using a third-order longitudinal mode, which is one method to release the stress concentration and to increase its lifetime of the original Rosen type [16]. Disk type transformers with an asymmetrical electrode pattern which have a much higher voltage step-up ratio than the rectangular type and disk multilayer types with a floating layer were proposed successively recently [17, 18].

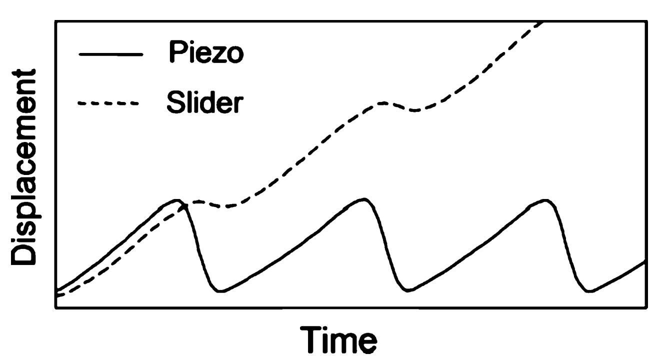


Fig. 6 Displacement of the piezo-element and the slider.[15]

Fig. 7 A piezoelectric pump water cooling module (*left*) for a fuel cell in a laptop computer.[Courtesy by NEC]

Noticing that the largest components in the circuit are electro-magnetic transformers, researchers at Penn State have been working in collaboration with Face Electronics on replacing these conventional EM transformers with high power piezoelectric transformers. Figure 8 shows a credit card size adaptor (35W) with a piezo-transformer, in comparison with the conventional EM type. Notice the size difference 1:5.

3.3 Printer

Epson commercialized a piezoelectric inkjet printer, by utilizing a co-firing technique of PZT with ZrO_2 substrates (see Fig. 9). This co-firing technique significantly improved stability in vibration for various inks during the patented pull–push–pull dynamic action of the piezoelectric chamber [19], as well as reduced the manufacturing cost drastically.

3.4 Optical fiber alignment

We are approaching Optical Communication era. However, compared with electric components, optical components such as fiber couplers, optical switches are expensive. Targeting 1/10 lower price, The Penn State Univ is developing simplest, inexpensive optical couplers, by

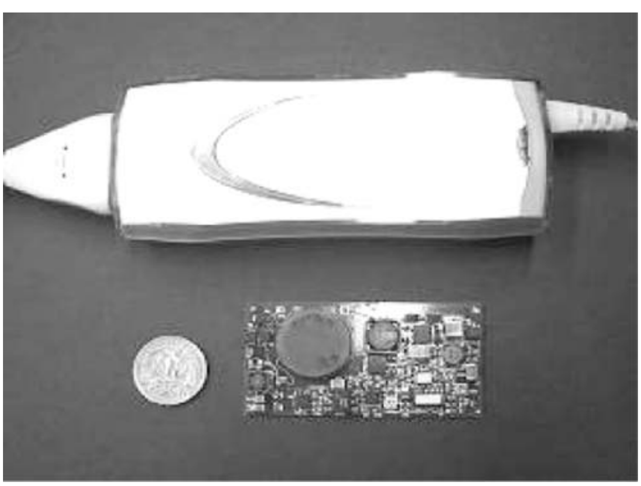


Fig. 8 Laptop computer adaptor with a piezoelectric transformer (bottom), in comparison with a conventional EM type.[Courtesy by Face Electronics]

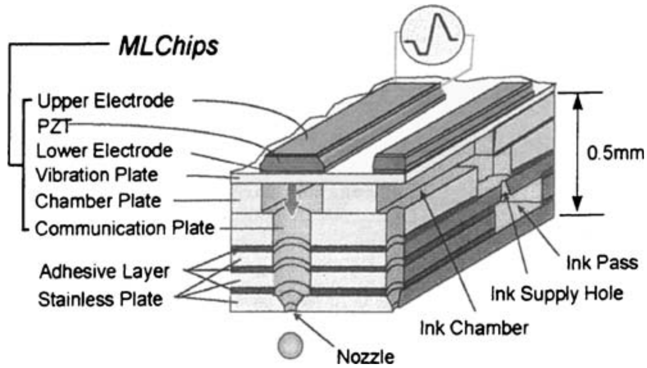


Fig. 9 EPSON MACH printer head structure.[19]

adopting linear USMs. The idea is to adopt the co-firing technique for whole optical switch, including a base package (Low Temperature Co-fire Ceramic, LTCC) and a linear motor (low temperature co-fire PZT). Two optical fibers are inserted into this package, and the fiber position is aligned by using a Λ-shape linear motor (see Fig. 10). Then, the fibers are fixed by immersing resin.

4 Robotics

Shape control, vibration damping, micro positioners and micro vehicles are typical application categories in robotics area.

4.1 Shape control

The US Air Force is developing “Smart Wings” for fighters by using ultrasonic motors. Coupled with an eccentuator mechanics, the Shinsei USM functions to control the wing shape (morphing) (Fig. 11) [20].

4.2 Vibration damping

Multilayer (ML) actuators are used for suppressing the body noise vibration actively on Euro-Rail trains (EADS)

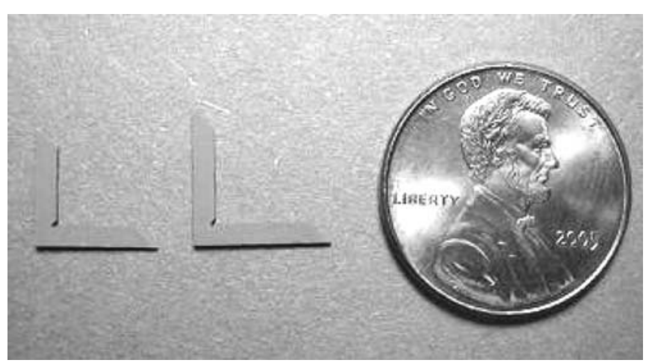


Fig. 10 Λ-shape linear motor fabricated by the LTCC compatible method at 900 °C.[Courtesy by PSU]

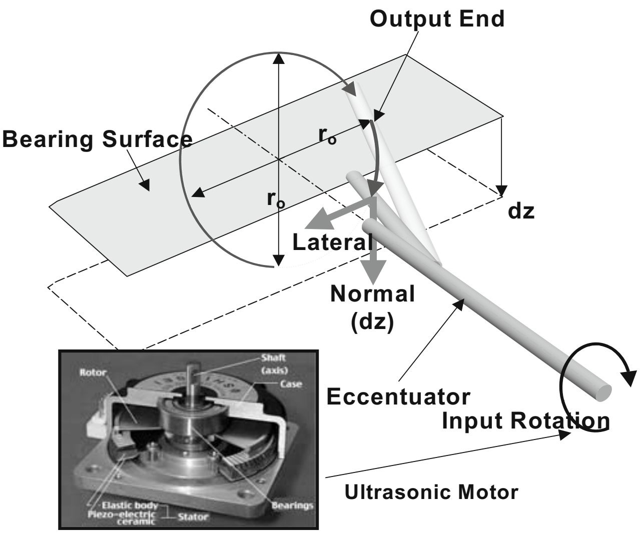


Fig. 11 Wing shape control with an ultrasonic motor and an eccentuator mechanism. [Courtesy by AFRL]

[7] and the US Army helicopters (QorTek & The Penn State) [21] (Fig. 12).

Vazquez Carazo and Uchino [21] introduced a compact drive system with piezoelectric transformers for these ML piezoelectric actuators. In this sort of military application, we need a compact, light-weight, electromagnetic-noise free system while keeping quick response (minimum 200 Hz). A thinly designed piezo-transformer was inserted into the unused space between ML actuators in Fig. 12(b). Figure 13 summarizes the drive system for piezoelectric actuator control. High AC voltage from the piezo-transformer was rectified, and this DC voltage was applied to the actuator through a Class-D switching power amplifier to control the applied voltage. This drive system could be used at least up to 500 Hz, which is sufficient for an active vibration control on a helicopter. Note that the new drive system is compact, light-weight by 1/10 in comparison with conventional electromagnetic transformer circuits, and magnetic-noiseless (transformer integrated actuator).

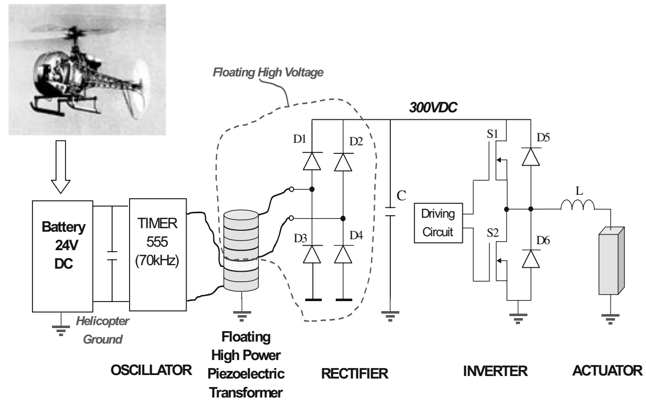


Fig. 13 Compact drive system with a piezo-transformer for piezoelectric actuator control.[21]

4.3 Positioner

Positioners are the most popular application of piezoelectric actuators. Multiple companies have already commercialized various stages. Figure 14 shows an example based on Physik Instrumente's rotary stage (USM type) [22].

4.4 Micro vehicle

The Penn State metal tube motors have been utilized in the world-smallest 4 WD vehicle (Fig. 15). Notice the index-finger print on which the vehicle is operated (the drive circuit and a battery are outside).

As you know well, Seiko micro motors have been used in wrist watches for silent alarm and perpetual function. The recent application by Seiko–Epson is found in a micro aerial vehicle. Figure 16 shows a micro flying robot, helicopter with the size 13 cmϕ, 7-cm height and 8.9-g weight, in which the floating force is obtained by two USM's and additional two motors provide the position/cant control [23].

Applied Micro Systems commercialized a micro robot shown in Fig. 17, which consists of four electromagnets (for clamping) and 4 ML actuators (for translation). The principle is "inchworm" motion on a steel surface with 30-nm movement resolution at present. Micro-tools such as

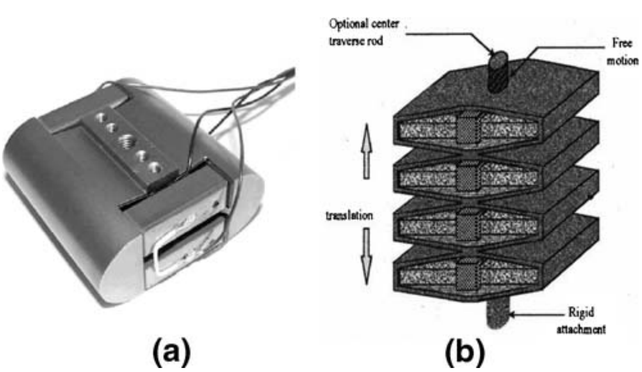


Fig. 12 Active vibration damping actuators with MLs. (**a**) for train body (EADS) and (**b**) helicopter (QorTek & PSU)

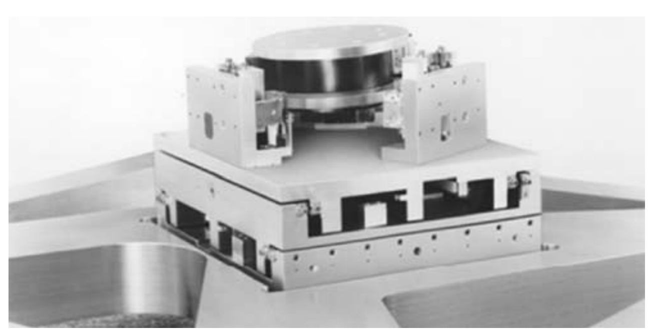


Fig. 14 Complex *x–y* rotary stage with USM. (Courtesy by Physik Instrumente) [22]

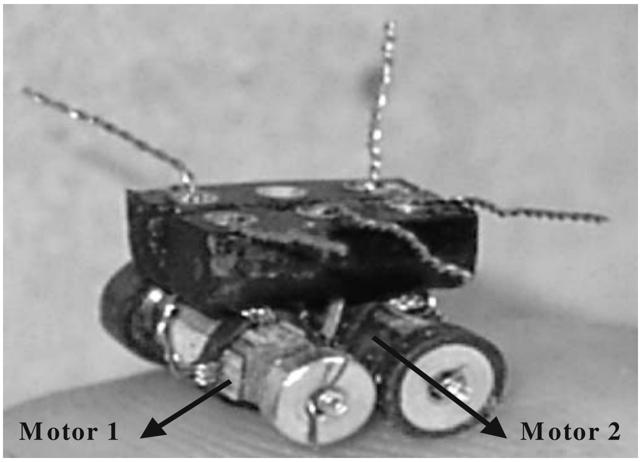


Fig. 15 World-smallest vehicle with two metal tube USM's

tweezers, scissors, drillers are available in conjunction with the robot base, for manipulating nano-particles and fibers [24].

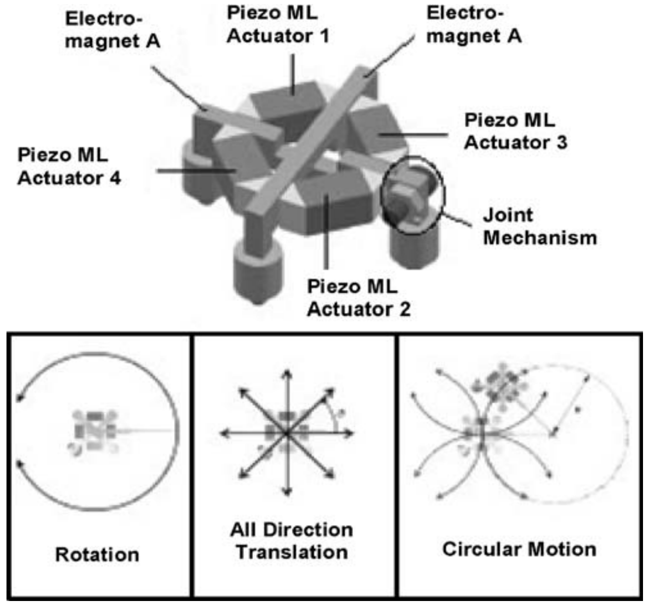


Fig. 17 Micro robot with four electromagnets and 4 ML actuators. (Courtesy by Applied Micro Systems)

5 Bio/Medical applications

5.1 Artificial fertilization system

Because of the high responsivity of the piezo-actuator in comparison with a normal hydraulic oil pressure system, sophisticated artificial fertilization systems were developed. Figure 18 shows the egg deformation difference during the needle insertion process for the previous micro robot usage and for the conventional oil-pressure system. It is obvious that the deformation can be minimized by using a piezo-actuation because we can superpose a 100 Hz high frequency motion onto the needle.

5.2 Micro medical pump

PZT thin films are deposited on a silicon wafer, which is then micro-machined to leave a membrane for fabricating micro actuators and sensors, i.e., micro electromechanical systems. Figure 19 illustrates a blood tester developed by Penn State in collaboration with OMRON Corporation in Japan [25]. Applying a voltage to two surface interdigital electrodes, the surface PZT film generates surface membrane waves, which soak up blood and the test chemical from the two inlets, then mix them in the center part, and send the mixture to the monitor part through the outlet. FEA calculation was conducted to evaluate the flow rate of

Fig. 16 Compact helicopter with micro ultrasonic motors. [23] (Courtesy by Seiko-Epson)

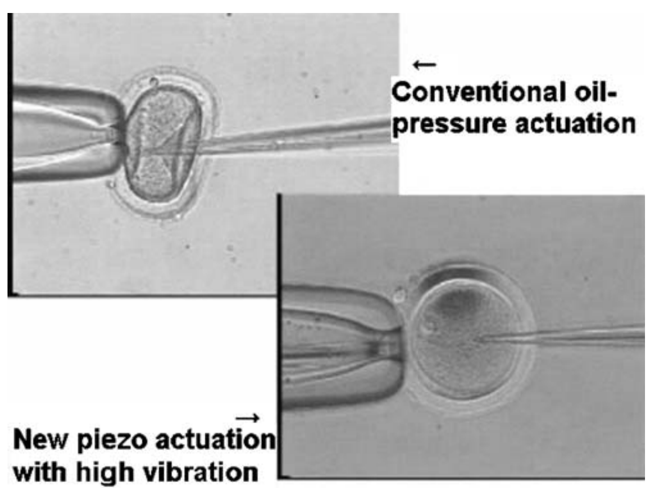


Fig. 18 Egg deformation during the needle insertion process for the piezo-robot usage (*bottom*) and for the conventional oil-pressure system (*top*;.Higuchi, website, Univ. of Tokyo]

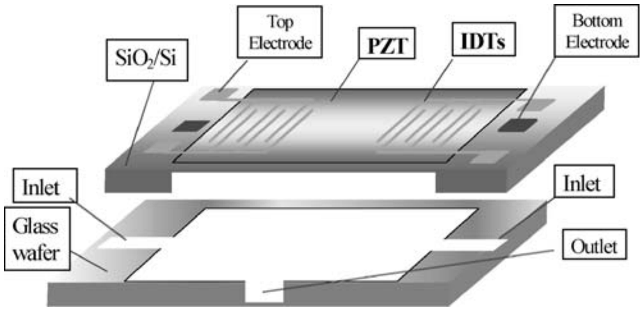


Fig. 19 Structure of a PZT/silicon MEMS device, blood tester[25]

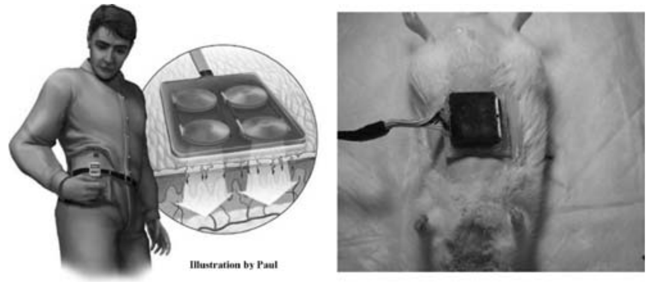


Fig. 21 Transdermal insulin drug delivery system (*left*) and its test procedure with a mouse (*right*)

the liquid by changing the thickness of the PZT or the Si membrane, inlet and outlet nozzle size, cavity thickness.

5.3 Micro surgery

Micro motors less than 3 mmϕ are very useful for the micro surgery or minimal invasive surgery. Univ of Washington, in collaboration with Penn State, is developing the sideview-monitoring endoscope/gastroscope, as illustrated in Fig. 20.

5.4 Drug delivery

High power ultrasonic is applicable to transdermal drug delivery. The Penn State researchers are working with commercialization of this "needle-free" injection system of insulin by using cymbal piezo-actuators (see Fig. 21) [26].

5.5 Ultrasonic distillation

Fundamental research on "Sono-Chemistry" is now very rapidly on going. Ultrasonic distillation is possible at room temperature for obtaining highly concentrated Japanese "Sake". Different from the regular boiling distillation, this new method makes "Sake" much higher alcoholic concentration with keeping gorgeous taste and fragrance. Figure 22 shows the alcoholic concentration in the base solution and mist (a) and their high-quality Sake product now commercially available (b; http://www.shumurie.co.jp.).

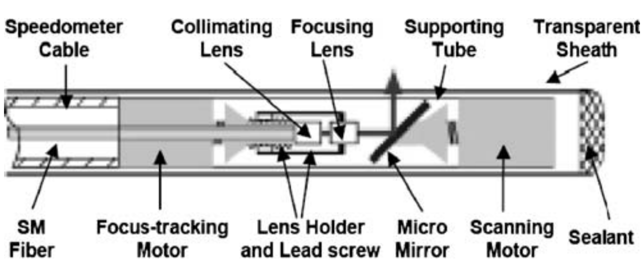


Fig. 20 Sideview monitorable endoscope with a rotating mirror driven by a metal-tube micro USM

6 Ecological/Energy areas

Twenty-first Century is called "The Century of Environmental Management." We are facing serious global problems such as the accumulation of toxic wastes, the Greenhouse effect of Earth, contamination of rivers and seas, lack of energy sources, oil, natural gas etc. Basically, we should regulate the usage of toxic materials, neutralize the toxic materials, first. Second, energy saving and new energy creation should be considered. Piezoelectric actuators with high efficiency are again highly respected from these viewpoints.

6.1 Lead-free piezoelectrics

Although famous PZT ceramic is rather chemically stable in practice, some people do not like Pb element. Thus, Japanese and European community may experience governmental regulation on the lead usage in these 20 years. Pb (lead)-free piezoceramics have started to be developed after 1999. Lead-free piezoelectric materials are classified into (1) piezoelectric single crystals, e.g., langasite ($La_3Ga_5SiO_{14}$) and lithium tetraborate ($Li_2B_4O_7$),

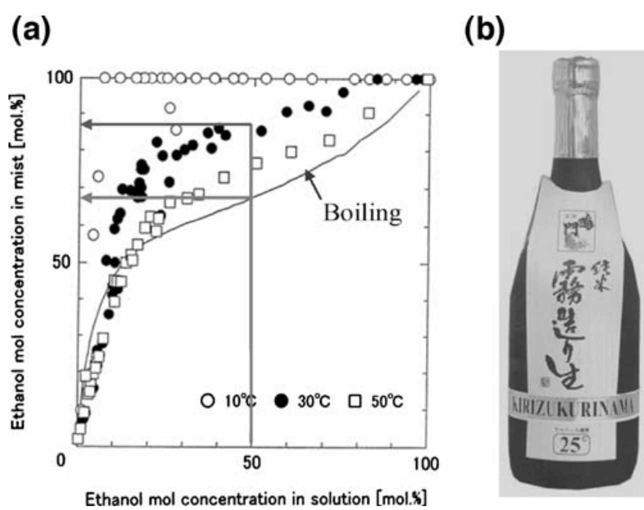


Fig. 22 Room temperature distillation with high power ultrasonic: (**a**) experimental results, (**b**) highly concentrated "sake" product. (Courtesy by Matsuura Brewer)

(2) tungsten broneze-typed ferroelectric ceramics, (3) bismuth layer structured ferroelectric ceramics, (4) potassium-sodium niobate, $KNbO_3$-$NaNbO_3$ systems, and (5) other perovskite-typed ferroelectric ceramics. Figure 23 shows statistics of various lead-free piezoelectric ceramics. The share of the papers and patents for bismuth compounds (bismuth layered type and (Bi,Na)TiO_3 type) exceeds 61%. This is because bismuth compounds are easily fabricated in comparison with other compounds. The most recent report on giant strain in a single crystal $BaTiO_3$ is also noteworthy [27]. Refer to the most recent review paper by Tsurumi [28].

6.2 Ultrasonic cleaner

Ultrasonic lens cleaner is commonly used in a home. Industrial ultrasonic cleaners are widely utilized in the manufacturing lines of Silicon wafers and liquid crystal class substrates. Honda Electronics added another ultrasonic cleaner in conjunction with a washing machine produced by Sharp. Figure 24 shows their L–L coupler horn to generate water cavitation for removing dirt on a shirt collar. It is noteworthy that we can reduce the amount of detergent (which is one of the major causes of the river contamination) significantly by this technique.

With increasing the power level of water cavitation, we can make hazardous waste innocuous, because the cavitation (cyclic adiabatic compression) generates more than 3000 °C locally for a short period. Hazardous wastes in underground or sewer water include dioxin, trichloroethylene, PCB, environmental hormone etc. As known well, dioxin becomes another toxic material when it is burned at a low temperature, while it becomes innocuous only when burned at a high enough temperature.

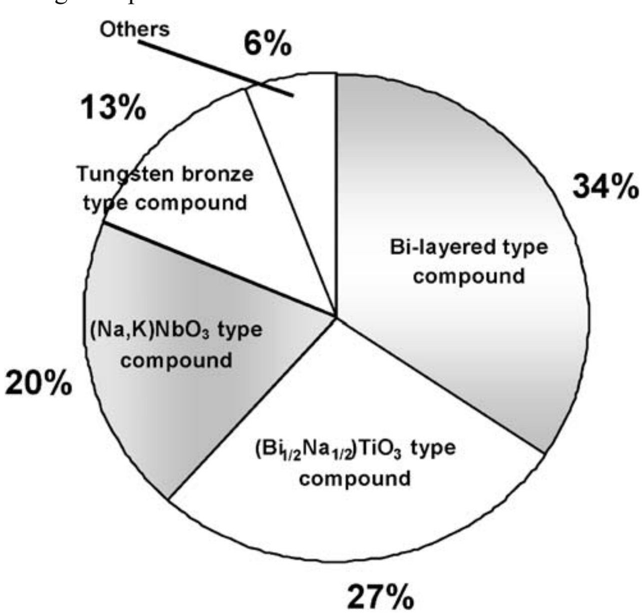


Fig. 23 Statistics of various lead-free piezoelectric ceramics. (Total number of patents and papers is 102)

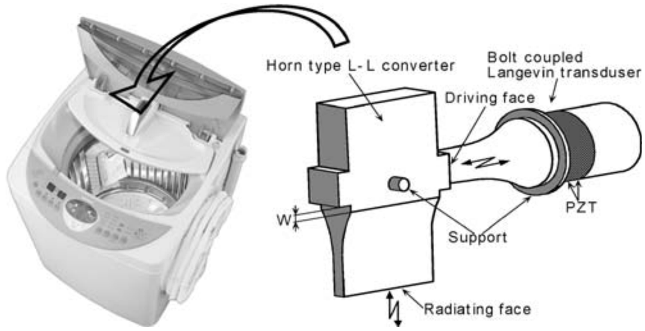


Fig. 24 L–L coupler horn for a washing machine application. [Courtesy by Honda Electronics]

6.3 Noise detection/Cancellation

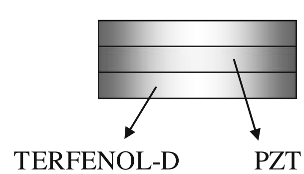
Mechanical noise (vibration and sound noise) and electromagnetic noise are also important environmental problems, nowadays. Automobile sounds should be cancelled in the residential area, and the magnetic field level must be checked at least under a high power cable line, because strong magnetic field may increase the human brain cancer. Kobayashi Institute of Physical Research developed curved PVDF large panels for the high way noise cancellation application. 30–40 dB reduction of sound noise was achieve around a low frequency range (100–300 Hz) compared with the regular concrete wall [29].

Similar to nuclear radiation, magnetic irradiation cannot be easy felt by human. We cannot even purchase a magnetic field detector for a low frequency (50 or 60 Hz). The Penn State, in collaboration with Seoul National University, developed a simple and handy magnetic noise sensor for these environmental monitoring purpose. Figure 25 shows a schematic structure of the device, in which a PZT disk is sandwiched by two Terfenol-D (magnetostrictor) disks. When a magnetic field is applied on this composite, Terfenol will expands, which is mechanically transferred to PZT, leading to an electric charge generation from PZT. By monitoring the voltage generated in the PZT, we can detect the magnetic field. The key of this device is highly effective for a low frequency [30].

6.4 Piezoelectric energy harvesting

One of the most recent research interests is piezoelectric energy harvesting. When a piezoelectric is adopted in a noise vibration system, cyclic electric field is excited. If this

Fig. 25 Magnetic noise sensor consisting of a laminated composite of a PZT and two Terfenol-D disks [31]



electric energy is consumed via a suitable resistor as Joule heat, mechanical noise vibration is significantly suppressed; that is, passive damper [31]. On the other hand, if the electric energy is accumulated into a rechargeable battery, a new energy harvesting system can be realized. Figure 26 shows an LED traffic light array system driven by a piezoelectric windmill developed by NEC-Tokin. Wind generated by passing automobiles is effectively utilized.

The Penn State group developed energy harvesting piezoelectric devices based on a "Cymbal" structure (29 mmϕ, 1–2 mm thick), which can generate electric energy up to 100 mW under an automobile engine vibration [32]. By combining three cymbals in a rubber composite, a washer-like energy harvesting sheet was developed for a hybrid car application, aiming at 1 W constant accumulation to a fuel cell. Figure 27 demonstrates soft-energy harvesting concept (Intelligent Clothing) with using a piezo-fiber composite, in collaboration with Smart Materials.

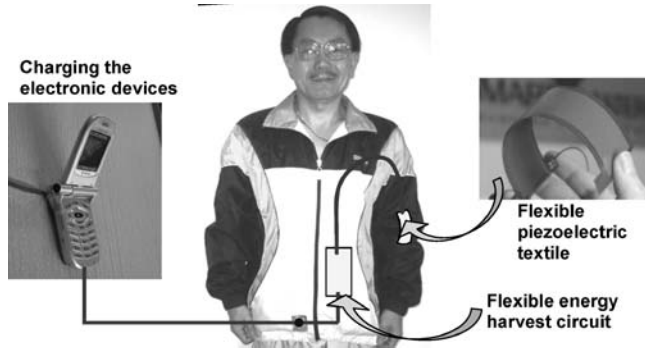


Fig. 27 Concept of soft energy harvesting; Intelligent Clothing with a flexible piezo-fiber composite

6.5 Diesel injection valve

Japanese Government tried to reduce the diesel engine vehicles previously in order to reduce toxic exhaust gases such as NO_x and SO_x. On the other hand, European Community is encouraging to increase the diesel automobiles, even by putting large efforts on developing sophisticated catalytic exhaust systems. The key reason in this political difference came from the consideration of "Total" energy required to realize unit drive distance for a vehicle (MJ/km). We should take into account both "Well to Tank" and "Tank to Wheel" energy as "Total" energy. Though the gasoline engine generates lower energy for "Tank to Wheel," higher (electric) energy is required to create high purity gasoline, compared to the diesel engine. In total, the diesel seems to be better. Further, CO_2 gas generation (one of the Greenhouse causes) per unit distance drive is larger for the gasoline engine (htt://www.marklines.com/ja/amreport/rep094_200208.jsp). Of course, just from the environmental viewpoint, electric cars with fuel cells will be the best. However, because very high investment is required to increase the mileage rate, electric cars are not realistic. The final target will be, in the author's opinion, hybrid cars with a fuel cell and a diesel engine (Not the present gasoline engine!).

In order to increase the diesel engine efficiency, high pressure fuel and quick injection control are required. Figure 28 shows an example of diesel fuel injection timing chart. In this one cycle (typically 60 Hz), the multiple injections should be realized in a very sharp shape. For this purpose, piezoelectric actuators, specifically ML types, were adopted. The highest reliability of these devices at an elevated temperature (150 °C) for a long period (10 years) has been achieved. So-called common-rail type injection valves have been widely commercialized by Siemens, Bosch and Denso Corp (Fig. 29) [33].

7 Future R&D trend

Future research trends will be divided into two ways: up-sizing in space structures and down-sizing in office equipment. Further down-sizing will also be required in medical diagnostic applications such as blood test kits and surgical catheters. The development keywords will be *integration* and *hybridization*.

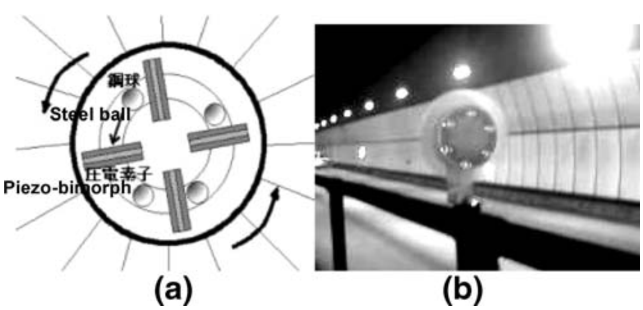


Fig. 26 Piezoelectric windmill (**a**) for driving an LEC traffic light array system (**b**) (Courtesy by NEC-Tokin)

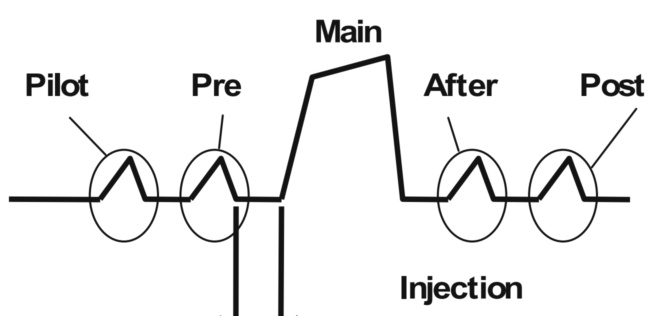


Fig. 28 Diesel fuel injection timing chart in one cycle (about 60 Hz cycle)

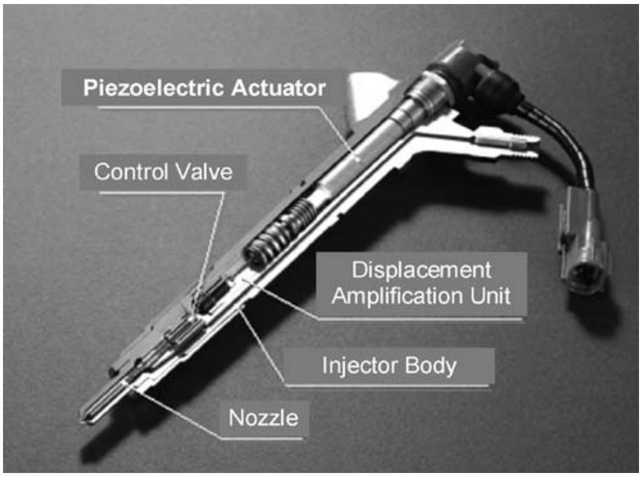


Fig. 29 Common rail type diesel injection valve with a piezoelectric multilayer actuator (Courtesy by Denso Corp)

Piezoelectric thin films compatible with silicon technology will be much focused in micro-electromechanical systems. An ultrasonic rotary motor as tiny as 2 mm in diameter fabricated on a silicon membrane is a good example [34]. One ceramic multilayer component actuator proposed by Mitsui Chemical is very suggestive for predicting the future trend [35]. Only by the external connection, a combined vibration of the longitudinal L_1 and bending B_2 modes can be excited. Compact ultrasonic motors such as Penn State's "windmill" and "metal tube" motors will expand the applications in medical diagnostic/surgical areas.

Miniaturization of the drive circuit will be also an important research area for the actual wide commercialization. Piezoelectric transformers may cause a breakthrough for this application. The piezo-transformer has input and output terminals fabricated on a piezo-device, and the input/output voltage is changed through the vibration energy transfer. In general, the size of piezo-transformer is 1/10 of the conventional EM transformer. Figure 30 exhibits a new ultrasonic motor with its drive circuit and a piezoelectric transformer integrated, which is directly driven by connecting a battery [36].

Fig. 30 Piezo-transformer integrated ultrasonic motor (Penn State).[38]

Next, we will foresee the application developments of the piezoelectric actuators. In the IT/office equipment application area, the development target is now how to reduce the production cost. ML actuators and USMs need to be manufactured less than US$3 per piece in these days. For the robotic applications, how the nano-technology is expanding, accordingly how nano-positioning is demanded will be the key to estimate the future market. In the bio/medical area, the price is not a very important factor, but the specs such as very low drive voltage and limited size are critical in designing. Pb-element is also hated when the instrument is inserted into a human body. Prosthetic arms and legs can be designed more sophisticatedly with USMs. Finally, environmental business is obviously expanding in these days. Accordingly, the demand for the actuators/transducers in the area is quickly increasing. Hazardous waste decomposition, ultrasonic cleaning and sono-chemistry are much more focused from now on.

Finally, with expanding the application field of piezo-actuators, the durability/reliability issue will become more important. The ultimate goal is, of course, to develop much tougher actuator ceramics mechanically and electrically. However, the reliability can be improved significantly if the destruction symptom of the actuator is monitored. Safety systems or health monitoring systems have been proposed with two feedback mechanisms: position feedback which can compensate the position drift and the hysteresis, and breakdown detection feedback which can stop the actuator system safely without causing any serious damages onto the work, e.g. in a lathe machine [37]. Acoustic emission and internal potential measurements, and resistance monitoring of a strain-gauge type internal electrode embedded in a piezo-actuator under a cyclic electric field drive are good predictors for the lifetime [38, 39].

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