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[Review Paper]

Next generation actuators leading breakthroughs

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Abstract

Conventional actuators still play the most important roles in motion control of automated machines. However, for advanced machines and instruments with higher performance, the conventional motors seem to be difficult to satisfy the coming sophisticated demands. So, the development of innovative actuators is recognized as one of the most important subjects of the key technology for next generation. Present state of the technology related to innovative actuators is introduced with some examples developed in a national project for new actuators. Essentials to develop a new actuator and to put it to practical use are also commented.

Keywords: Actuators; Artificial muscle; Electrostatic actuator; Micro actuator; Piezoelectric actuator

1. Introduction

Conventional motors driven by electromagnetic force have been playing and will still play the most important roles in motion control of automated machines like robots. However, for the advanced machines and instruments with higher performance, the conventional motors seem to be difficult to satisfy the coming sophisticated demands. And new outstanding actuators are expected to cause technological innovations in such broad fields of their applications as industry, basic science, medicine, welfare, and global environment. So, the development of innovative actuators is recognized as one of the most important key technologies for the next generation.

In accordance with the requirement, the five year national research project "Next-Generation Actuators Leading Breakthroughs" was organized and granted by the Ministry of Education, Culture, Sports, Science and Technology of Japan. This five year national research project started in September 2004 and finished in March 2009.

Since development of innovative actuators requires a comprehensive and interdisciplinary approach, the project was conducted by many researchers from various fields such as mechatronics, robotics, control engineering, MEMS, new material, processing, production technology, and bio technology as shown in Fig. 1.

The project was operated cooperatively by the following five research groups: (1) High precision actuators for small motion of nano-meters, (2) Small-size actuator of micro-meters structure, (3) Intelligent actuators for functional motion, (4) Power actuators, for large force/torque, and (5) Actuators for special environments. Each group consists of about eight subjects. So, over 100 researchers joined the project. To seek the applications of the new actuators, research and development of some subjects has been propelled in cooperation with industry.

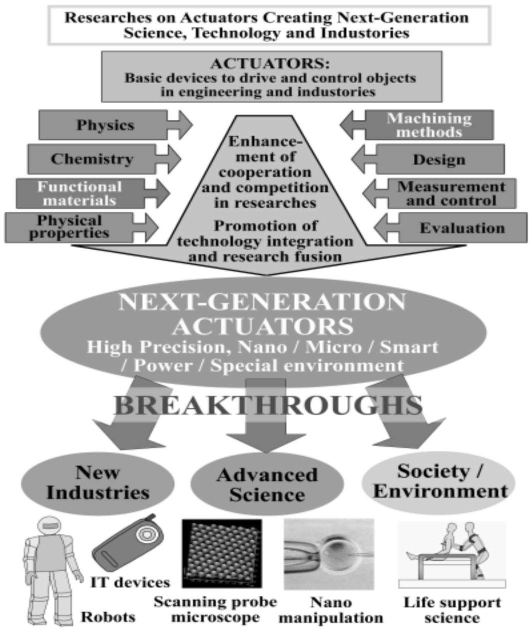

Fig. 1. Illustration of the project for new actuators.

In this national project, comprehensive research was per-

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formed with such actuators as powerful electrostatic actuators, various kinds of micro actuators, surface acoustic wave motors, ultrasonic motors, bio-actuated micro pump, intelligent actuators, pneumatic soft actuators, polymer ion gel actuators, piezoelectric actuators, thermal actuators, magnetostrictive actuator and multi-degree of freedom motors. The accomplishment of the project will be published in a reference book [1].

This article presents an overview of new actuators, by introducing some of research works of the project. And as an example of the new actuators, a powerful electrostatic actuator that has been developed by the research group of the author is introduced with some applications.

Based on the experience as the leader of the project, I also would like to give some remarks about how to invent a new actuator, and how to put it into practical use.

2. Overview of new actuators

2.1 Micro and nano actuators

Accompanying the growth of MEMS (micro electro mechanical systems), many kinds of micro actuators have been developed. As prominent rules of physics in the small-scale world are different from those of normal size, invention of new principle of actuators is expected for micro and nano actuators. For example, electrostatic force, deformation related to heat, and PZT [2] have been applied to the drive mechanism of micro actuators. The micro actuator has such an advantage that it is allowed to employ various kinds of materials, since the cost of material is not so serious in micro actuators.

Electro-conjugate fluid (ECF) is a kind of functional fluid that generates jet flow in high inhomogeneous electric field. Micro motors driven by ECF jet [3] are shown in Fig. 2.

We should also pay attention to the research activity related to nano structure like carbon nanotubes. Research of the mechanism of muscle and driving mechanism of very small creatures gives us a clue for a new nano actuator. Manipulation of small objects is also important technology necessary for assembling micro machines and for processing cells [4].

2.2 Actuators using piezo elements

The success of STM(scanning tunneling microscope) and AFM proves that we can manipulate probes and specimens at an atomic scale. To get precise positioning with a resolution of from several nanometers to sub microns, piezoelectric elements are the most useful actuators. The STM probe should be positioned with the resolution of nm, even angstroms. Now only piezoelectric elements can satisfy the requirements commercially. As for the frequency response, a piezo element itself can deform much faster than usual electric linear motors like a voice coil motor. So, the piezoelectric element seems to be the most convenient actuator when we need to position a rather small object with high accuracy. On the other hand, the maximum deformation of a piezo element itself is limited to very small, like 10 micrometers for a 10 mm long piezo element.

Since the displacement of a piezo itself is limited, several methods have been developed to realize longer or boundless movement by combining some mechanism with piezo elements. The typical mechanisms are "inchworm," "impact drive mechanism," [5] and ultrasonic motors [6]. As piezo elements can be used also to generate vibration of high frequency, the driving mechanism of ultrasonic motors has been developed for continuous rotation and long distance movements. Since ultrasonic motors have the property of low speed and high torque motors, they are suitable for direct drive applications.

By using SAW (surface acoustic wave), a new type of ultrasonic linear motor was developed. The structure of SAW motor is shown in Fig. 3. It can achieve acceleration of a mover at 1000 G and positioning with resolution of several nanometers [7]. This new thin linear motor has the possibility to be used for head access mechanism of a future disk memory.

As the material of piezo element, PZT(lead zirconate titanate) is widely and commonly used to obtain a large piezoelectric constant. Since PZT contains lead that should be eliminated from all consumer goods, development of lead-free piezo elements with good property for actuators becomes a serious and urgent problem [8, 9, 10].

2.3 Artificial muscle and muscle like actuators

The most interesting subject in the next decade related to robotics is realization of humanoid robots. To complete the ultimate robots that can think and act exactly like humans, we have to develop many new technologies. One of the most important elements for motion control of humanoid robots is such actuators that can work like muscles. Muscles of animals have some splendid properties that have not been obtained by the ever-developed actuators. Compared to the usual electrical motors, human muscle has the following advantages.

(1) High efficiency of energy conversion - Coolness
(2) High power density and lightweight - Lightness

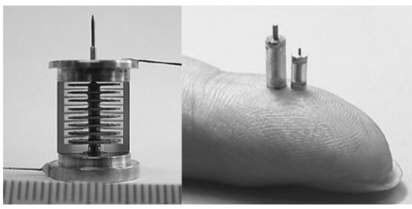


Fig. 2. ECF micro motors.

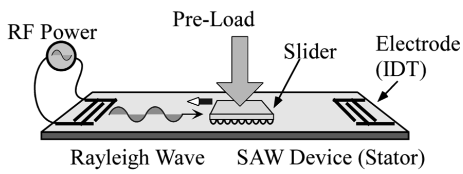


Fig. 3. Surface acoustic wave motor.

(3) Elasticity and softness of its structure - Softness
(4) Self-diagnosis and self-repairing - Toughness

Since the mechanism of the human muscle has been investigated profoundly at the molecular scale, we should develop such an actuator of which the mechanism is similar to the muscle where numberless micro energy-conversion units are accumulated. Electrostatic actuators, polymer actuators [11, 12], ultrasonic motors, shape-memory alloy actuators, and pneumatic actuators have the possibility to advance to the muscle-like actuators.

As most of these muscle-like actuators are soft actuators, they are suitable to install in the power assist system [13]. The structure and the photo of a power assist glove by pneumatic rubber artificial muscles developed by Noritsugu is shown in Fig. 4.

2.4 Actuators in unconventional environments

According to the advancements of science and technology, the use of unconventional environments such as super-clean, ultra high vacuum, high temperature and cryogenic environment must be increasing. For the material handling and processing in the unconventional environments, conventional electric motors do not always act well. We have to develop new actuators that are suitable for these severe environments.

As a permanent magnet loses its magnetic potential at Curie temperature, conventional electromagnetic actuators are difficult for use in high temperature. New kinds of actuators for high temperature should be developed by applying new materials or by devising new mechanisms.

As for shape memory alloy actuators, new materials which can work in cryogenic condition [14] and in high temperature [15] have been developed.

Unconventional environments do not always restrict the conventional methods but sometimes give us means that can work well only in the severe environments. For instance, in cryogenic environments, we can utilize super-conductive material for coils of motors without heat loss and for magnetic bearings and levitations.

The demand for the actuators that do not contaminate a super-clean environment and vacuum is increasing in such fields as semiconductor processing, biotechnology and pure processing of new materials. Since fine particles and contaminants are generated mainly from bearings, ball screw, and guides of slider, actuators without mechanical contacts should be developed for super clean use. Lubricants should be also eliminated from the actuators. Combination of direct drive motors and contact free bearings like magnetic bearings is a typical solution [16]. In the case where a magnetic field is avoided, electrostatic motors combined with electrostatic levitation seem to be promising [17]. Especially in vacuum, higher electrostatic field can be used than in normal air. Our group succeeded in electrostatic levitation of aluminum plate of 20 mm thickness in vacuum.

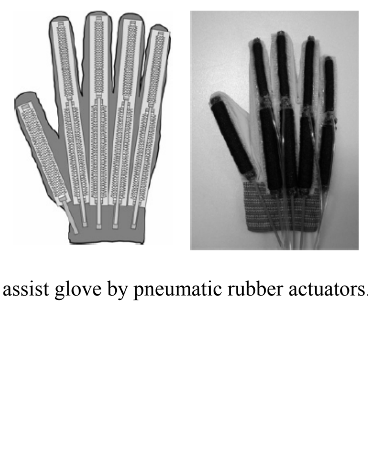


Fig. 4. Power assist glove by pneumatic rubber actuators.

3. High-power electrostatic film motors

3.1 Structure and principle of the electrostatic motor

The basic structure of the electrostatic motor, shown in Fig. 5., consists of a pair of thin plastic films that function as slider and stator, respectively. Both films are made using flexible printed circuit (FPC) technology. In both of them, three-phase parallel electrodes, which are aligned with regular intervals like 200 μm, are fabricated [18, 19].

Normally, the two films are just simply stacked without using linear guide; thus, two films are in direct friction when the motor operates. Since such direct friction causes considerably large loss of thrust force, glass beads with diameter of 20 μm are often inserted between films to reduce friction.

How the driving force is generated is shown in Fig. 6. By applying three-phase sinusoidal voltage to the three poles of the slider and stator, two potential distributions traveling in opposite directions are excited. The interaction between those two distributions actuates the slider, so that the spatial phase difference between two distributions is kept at stable phase. This causes the slider to run twice as fast as potential distributions.

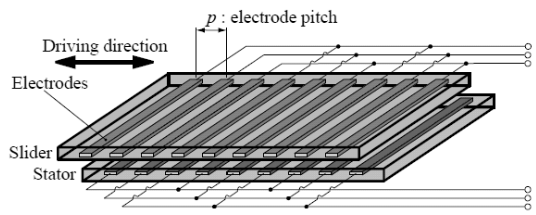


Fig. 5. Structure of the electrostatic motor.

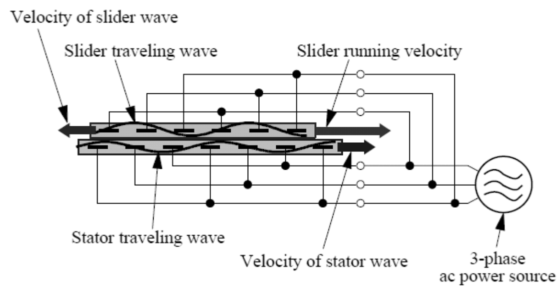


Fig. 6. Driving principle of the electrostatic motor.

Thrust force is proportional to square of amplitude of applied voltage. It can operate from the lowest applied voltage of around 500V. However, to obtain practical force, it requires higher voltage than 1kV. With such a high voltage of over 1kV, electric discharge may occur in the atmospheric air, which disturbs the electrostatic field inside the motor and causes improper motor behavior. To prevent such discharge, a dielectric liquid like Fluorinert is used for insulation.

3.2 Stacked motor configuration

The force output capability can be easily increased by stacking many pairs of slider and stator films as shown in Fig. 7. With the same applied voltage, thrust force is proportional to overlapping electrode area between slider electrodes and stator ones, which can be increased by stacking many pairs of films.

Motor housings are typically made of plastic to avoid the risk of electric leakage. Some examples of such are shown in Fig. 8. 50-layer stacked films are contained in a plastic package as shown in Fig. 8(a). Fig. 8(b) is a plastic film package, which has flexibility. In some prototypes, metal housings were utilized to enhance overall stiffness for precise positioning.

3.3 Performances of the motor

The most important index in performance is thrust force per unit area of the electrode film. An example of thrust force per unit area measured by weight-pulling-up experiments is plotted in Fig. 9. The thrust force is almost proportional to squared applied voltage as shown in Fig. 9. The stacked motor shown in Fig. 8(a) generates thrust force over 310N. And the maximum velocity of 1m/s is obtained. By using a precise position sensor, position control of several nano meter resolution can be achieved.

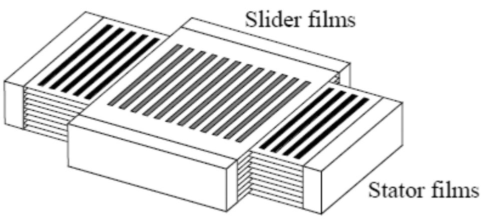
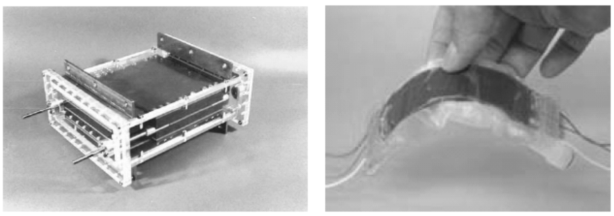


Fig. 7. Stacked motor configuration.



(a) (b)

Fig. 8. Examples of housings of stacked motors.

3.4 Applications of the electrostatic motors

3.4.1 (a) Robot arms [20]

A 2-DOF robotic arm driven by the electrostatic motors is shown in Fig. 10. The frame of the robotic arm is fabricated using cylinders of acrylic plastic. The total length of the robotic arm measures 500 mm. The total weight is approximately 320gf. On each rotating shaft of the joints, a potentiometer is equipped to detect the joint angle. The robotic arm has two types of the electrostatic motors. In the upper arm, a round bent stacked motor is installed. In the forearm, a pair of motors constructs antagonistic muscle-like structure.

3.4.2 Fish robot [21]

To control the motion of the caudal fin of a fish robot, an electrostatic film motor is installed as shown in Fig. 11. The robot fish can turn smoothly by shifting the neutral position of the oscillation of the sliders.

3.4.3 Flexible actuator

The electrostatic film motor can work well even when it is bent in any direction as shown in Fig. 12. So, the film motors are able to be installed in a narrow space.

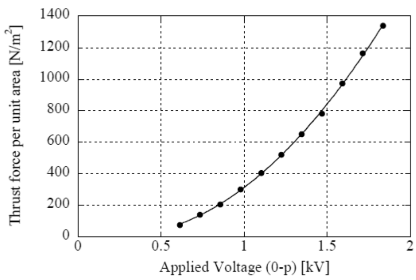


Fig. 9. Thrust force per unit area.

Fig. 10. Robot arm using electrostatic motors.

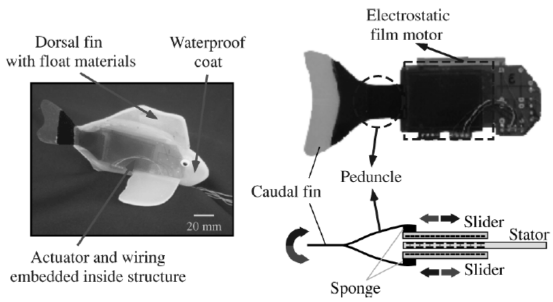


Fig. 11. Prototype of electrostatic fish robot.

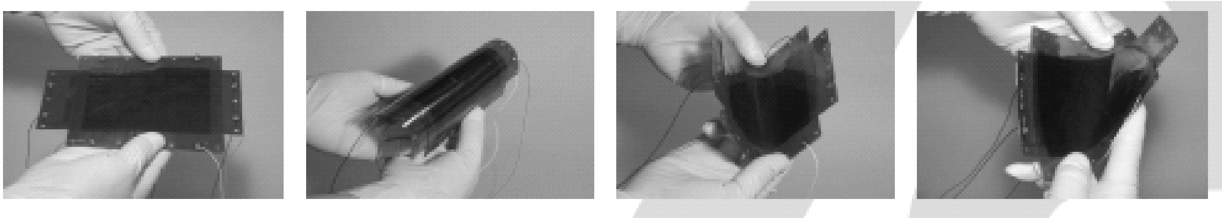


Fig. 12. Flexible motor working in various shapes.

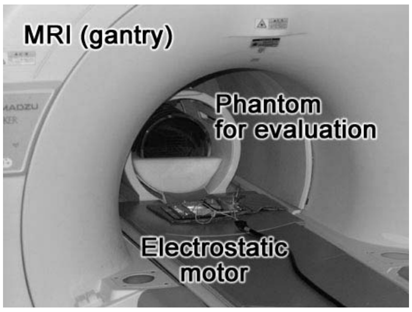


Fig. 13. Electrostatic motor working in MRI scanner.

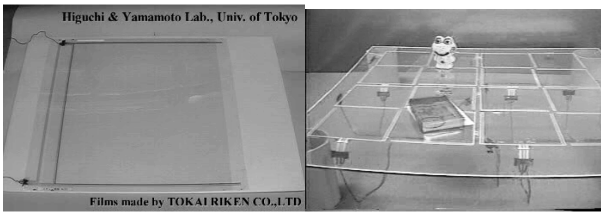


Fig. 14. Transparent actuator and moving display.

3.4.4 MR compatible actuator

A prototype motor was fabricated using non-magnetic materials and tested in an MRI scanner, as shown in Fig. 13. The generated force of the electrostatic motor was not degraded by the strong magnetic field [22]. As the current of the motor is small, the electrostatic motor gives negligible influence to the image of a sample in an MRI.

3.4.5 Transparent actuator

By using ITO as the material of the electrode, a transparent electrostatic motor can be made as shown in Fig. 14. The transparent motor is expected to apply as moving display for advertisement.

4. How to develop new actuators

4.1 Invention of a new actuator

To develop a new actuator, we have to invent or find a new principle of drive mechanism in which conversion to mechanical energy from other energy like electrical energy and chemical energy is accompanied. In addition to the knowledge of electromagnetism, mechanical engineering, and control engineering, comprehensive understanding of chemistry, biology, and material is necessary for creating a new method of actuation. Especially, the performance of actuators is dominated by the property of materials. We have to watch the progress and innovation of materials. For instance, a big evolution must occur in electric motors when room-temperature superconductive material emerges. Reevaluation of abandoned ideas proposed in old times may yield a new valuable actuator by applying recent technology.

4.2 Importance of production engineering

Production technology to provide the new-developed actuators with an appropriate cost is also important to be accepted in the market. For example, printing technology has been tried to produce electrodes of electrostatic actuators.

4.3 Control and drive system

Since sensors and power drivers are indispensable to control the actuators, we have to develop these elements to achieve good performance. To provide a small driving system, not only an actuator but also its driving circuit, sensor, and power amplifier should be made small. For example, more miniaturized positioning mechanism of lens for a tiny camera in a mobile phone is strongly requested. For these applications small and light position sensors are also required. And the actuator should be operated with low voltage battery cell with low-power-consumption.

4.4 Standardization of evaluation

To make an innovative actuator for common use, standardization of tests of performance is necessary. We have to develop measuring methods to evaluate the actuators. For instance, how to measure a tiny torque of an actuator is an important issue among the researchers of micro actuators.

5. Conclusions

Actuators will keep playing very important roles in advanced mechatronics in this century. Since research and development of actuators is related to various fields, cooperative research projects organized by universities and industry should be propelled for innovations of actuators by developing the "Next-Generation Actuators Leading Breakthroughs" project.

International collaboration of research and development for innovative actuators is also necessary to cope with rapid and extensive demands.

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