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Recent Development of Dielectric Elastomer Transducers and Potential Applications

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Abstract

Power generation using dielectric elastomer transducers is cheap, light, stackable, easy to install, and highly efficient. Also, since the dielectric elastomer transducer is an actuator developed into an artificial muscle, if the DE motor is further developed, it might be possibly be able to drive a vehicle. Efficient robot driving, various industrial machines and the use of dielectric elastomer sensors to optimize the driving may also help solve the above problems from the perspective of eco-driving. This paper describes the latest level of development of dielectric elastomers, their main problems and solutions to these problems, and their potential applications. The possibilities and concrete plans for building local global smart cities (including local generation power for local consumption), efficient transportation, and environmental monitoring systems utilizing dielectric elastomers are also discussed.

Keywords

High-Efficiency Power Generation, Lightweight and High-Output Actuator, Sensor with Wide Measurement Range, Flexible, SWCNT Spray

1. Introduction

There are many problems, such as global warming, population growth, and food production and delivery disruptions due to war, affecting the world today. In order to help solve these problems, research on carbon recycling, artificial photosynthesis, undersea carbon dioxide storage, underground storage, implementing energy conservation and renewable energy, etc., should be accelerating. Attempts have also been made to increase tree numbers, improve agricultural efficiency, and cultivate food and fish in urban buildings. However, the speed of research and development in the areas has not been as rapid as expected, nor has the amount of power generated by renewable energy increased as expected. On the contrary, mankind is moving toward greater power consumption. The first and foremost solution to these problems is to use renewable energy to produce a stable and low-cost electricity supply in large quantities.

There are various types of renewable energy, including wind power, wave power, photovoltaic power, solar thermal power, water current power, waste heat power, chemical/biomass power, geothermal power, and snow and ice power. Almost all experimental/demonstrational power generation and commercial power generation uses electromagnetic induction, and the generators are rotated by mechanical energy. Specifically, mechanical energy, for example, the force obtained from wind, falling water, stream currents, temperature differences, etc., drives a turbine to produce electricity. However, conventional generators using electromagnetic induction tend to operate most efficiently in a narrow range of high frequencies, which may not be suitable for renewable energy sources [1]. Renewable energy sources typically produce motion over a wide range and at low frequencies, so power generation systems using electromagnetic induction must include mechanical or hydraulic transmissions, making the system more complex, expensive and much more costly to repair [2]. Larger waves, wind power, water drops, temperature differences, etc., are required to generate power more efficiently, resulting in lower efficiency and higher power generation costs.

DEs (dielectric elastomers) are one of the promising artificial muscle technologies, and a new transducer that can convert mechanical energy into electrical energy. Compared to conventional generators that use electromagnetic induction or piezoelectric effect, DE generators (DEG) have high energy density and can generate power efficiently at low frequencies [3]. In fact, the performance of recent DE power generation is approaching the efficiency of coal-fired power generation, attracting a lot of attention worldwide. Similarly, as an actuator, it is the best fit for energy saving because it is light and can be driven with high efficiency. A DE actuator (DEA) can lift a weight of 8 kg with 0.15 g of DE by more than 1 mm at 88 msec, and has great potential for ultra-lightweight and ultra-high performance motors [4]. With this, it seems that it could well be within the range of possibility to run a car with a DE motor. In addition to these, DEA or DE sensors (DESs) use an electrode that can sufficiently light an LED even if the DE is extended by several hundred percent [5].

In this paper, a wide variety of issues including materials, electrodes, circuits, systems, durability, and their problems with recent DE transducers (DEG, DEA, DES) are explained. Furthermore, this paper discusses solutions for the problems and discusses global smart cities (local production areas) using DEs, including power consumption and methods of efficient transportation.

2. Background of Dielectric Elastomers (DEs)

The development of dielectric elastomers (DEs) began in 1991 as an artificial muscle using electricity at SRI International (Stanford Research Institute) in the

United States [6]. Since then, development has been continued all around the world.

The development of artificial muscle though a chemical approach began in 1949 with an actuator that relies on the movement of ions in a polymer gel [7] [8]. Actuators using ionic polymer-metal composites and conductive polymers to electrically transfer ions have also been developed [9] [10]. In addition, development of actuators using carbon nanotubes (CNT), heat, light, liquid crystals, air, and shape memory alloys is also underway [11]-[18].

However, the DE is becoming the mainstream in terms of performance, because it is superior. The development of actuators using piezo elements is also underway, because piezo elements have output, but because the piezo itself is hard, it has little stretch and cannot be called a muscle [19].

The structure of the DE is simple, consisting of an actuator sandwiched between flexible electrodes above and below an elastomer (polymer). When a voltage is applied to the electrodes, the upper and lower electrodes are attracted to each other by the Coulomb force, crushing the elastomer, and as a result, the elastomer is stretched horizontally, forming a linear actuator [20]. Expressing the pressure at that time in the formula;

This pressure, p, is

$$p = \mathcal{E}r\mathcal{E}oE^2 = \mathcal{E}r\mathcal{E}o\left(V/t\right)^2 \tag{1}$$

where $\mathcal{E}r$ and $\mathcal{E}o$ are the permittivity of free space and the relative permittivity (dielectric contact) of the polymer, respectively; E is the applied electric field; V is the applied voltage; and t is the film thickness.

The DE power generation can be expressed by the following formula.

The energy output of a DE generator per cycle of stretching and contraction is

$$E = 0.5C_1Vb_2\left(C_1/C_2 - 1\right) \tag{2}$$

where C_1 and C_2 are the total capacitances of the DE films in the stretched and contracted states, respectively, and Vb is the bias voltage.

As can be inferred from the above formula, DE research can be classified into research and development of materials (electrodes and elastomers), development of circuits that drive DEs, and research and development that integrates them into actuators. The development of materials depends on the type of elastomer to be used (including those that can be used at high temperatures and those that can be used at low temperatures), and the addition of substances with high dielectric constants to improve the dielectric constant of elastomers. There is research into various areas such as the influence of the thickness of the elastomer, the viscoelasticity of the elastomer, the cross-linking agent, the low voltage drive, the lifetime of the elastomer, the strain relief of the elastomer due to rolling or casting and the pre-stretch of the elastomer.

The development of the electrodes is diverse, and includes thin metal foils, liquid metals, carbon grease, carbon black, and carbon nanotubes.

Representative research on DE drive/generation circuits involves switching between series and parallel configurations using switching circuits and capacitors, the methods of voltage conversion, the effects of leakage current, and on passive circuits using diodes (mainly for power generation), etc. [5] [21] [22] [23] [24] [25].

System developments include dielectric elastomer geometries and their combinations. It is best to match the shape of the DE to the application. For example, as a linear actuator, output is increased by stacking and driving DE sheets [26] [27]. A roll-type DEA, which is a rolled DE sheet, is ideal for human prosthetic arms and legs, as well as for robot arms and legs [28]. Furthermore, the DEs is normally stored horizontally, but when driven, there are diaphragm actuators that move vertically [29]. For certain applications, the optimal system made possible by combining them well.

3. Problems of Dielectric Elastomers and Their Possible Solutions

Here, the problems of DEs and their possible solutions are discussed.

3.1. DE Power Generator

One widely known electromagnetic induction generator is a device that uses the phenomenon of electromagnetic induction, in which an electromotive force is induced in a conductor when a conductor such as a coil moves in a magnetic field. In this electromagnetic induction phenomenon, electric charges are constantly moving while the conductor is moving in the magnetic field, so even if a load such as an LED is always connected to the generator, electric energy can be obtained. For this reason, it is widely used as a power generation device that can easily obtain electrical energy. However, as mentioned previously, this electromagnetic induction phenomenon drastically reduces the electric energy obtained when the speed at which the conductor moves in the magnetic field decreases. For this reason, in power generation systems that use linear energy sources such as wind power, water power, and wave power, a structure that maintains speed is essential, which leads to a decrease in power generation efficiency.

A generator using a DE is a device that utilizes a phenomenon in which the electrostatic energy stored in a variable-capacitance capacitor increases as the capacitance of the capacitor decreases [29]. Since the power generation phenomenon using this electrostatic energy does not depend on the speed at which the capacitance changes, it is possible to construct a power generation system using wind, water, and wave power with a simple structure [30] [31].

In this way, a power generation system using DEs differs greatly from a general electromagnetic induction power generation system in that it uses electrostatic energy. Electrostatic energy acts as electrical energy only when the electric charge flows. Therefore, when a load such as an LED is continuously connected, the electric charge is lost before the electrostatic energy increases, so it cannot operate as a generator. In order to operate as a generator, it is necessary to have a means of conversion into electrical energy only when the electrostatic energy is at its maximum. Unfortunately, few people understand this phenomenon unique to electrostatic energy [31]. In addition, electrostatic energy is high voltage, and the fact that even voltage cannot be measured accurately with general measuring instruments is considered to be a major barrier. For example, 1 MΩ is a relatively high resistance in low voltage circuits, but 1 MΩ is not a very high resistance value in high voltage circuits. Considering Ohm's law, this is a matter of course, but there are papers that do not recognize this fact. The impedance of experimental equipment and measurement systems is an important factor in accurately measuring voltage and current. These might be the reasons many researchers are unable to capture this phenomenon well.

3.2. Problems and Improvements of Circuits Generating High Voltage for DEs

Many DE applications use high voltages of 1000 V or higher. Piezoelectric elements, which were once actively researched and developed, sometimes use relatively high voltages, of around several hundred volts, but applications using voltages of 1000 V or more are still not common. The parts that can be used for circuit design are limited. In particular, many semiconductors that support high voltages can handle high currents and have large losses, so they are not suitable for DE applications.

One way to overcome these problems is to use multiple tiers of devices with a withstand voltage of several hundred volts. A typical example is a high voltage generation circuit using the Cockcroft-Walton circuit. This circuit uses an AC wave or pulse wave of several hundred volts, and by repeating multiple stages, it is possible to generate a DC high voltage of several thousand volts or more.

Capacitors and diodes, which are the main components, can use devices of several hundred volts. **Figure 1** shows a high-voltage generator circuit using a Cockcroft-Walton circuit used in headphones equipped with a commercially available DE vibrator [32] [33].

In this figure, the part shown in the red frame is the high voltage generation circuit using the Cockcroft-Walton circuit. It is a 3-stage Cockcroft-Walton circuit because it consists of 6 capacitors and diodes. Since the applied voltage to

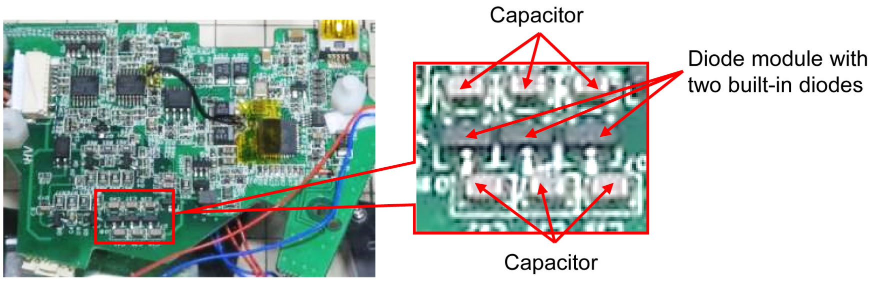


Figure 1. Circuit board for headphones with a DE vibrator.

the DEA is 1.2 kV, the AC wave applied to the circuit is expected to be about 400 V. Chip parts are utilized for the areas where price and mass production are a concern. Other circuits are audio circuits and equalizer circuits, which making up the majority of the total.

This high-voltage generator circuit using the Cockcroft-Walton circuit can be used as a drive power supply for the DEA and also as an initial voltage supply source for the DEG. However, when used in a DEG system, using an AC wave or pulse wave oscillator circuit that requires an external power supply is a disadvantage. There is also a method of combining it with a solar battery, but its range of use is limited because it is affected by the hours of sunlight. One way to overcome this is to combine it with piezo power generation [34] [35]. Piezoelectric power generation can generate pulsed AC waves by applying mechanical force to a piezoelectric element [19]. Since the generated voltage is relatively high, ranging from tens to hundreds of volts, it can be used as an oscillator for high voltage generation circuits using Cockcroft-Walton circuits. It is known that when a DEG is generated, a higher power can be obtained by applying a bias voltage first [20]. **Figure 2** shows the results of measuring the power generation amount for 50 minutes using two types of bias voltages in a DEG buoy power generation experiment conducted in the actual sea shore area. An electric energy of 14 J was obtained at a bias voltage of 1900 V, and about 30 J at a bias voltage of 3000 V. In this way, having a piezo makes it possible to build a DEG system that can generate electricity efficiently without an external power supply (including batteries).

3.3. Charging Circuit for Secondary Battery

A small DEG device can generate power efficiently even with a small amount of force and gentle movement, so it is suitable for small-scale power generation systems using renewable energy, and can also be used as a power source for various sensor systems. In general, small-scale power generation systems that use

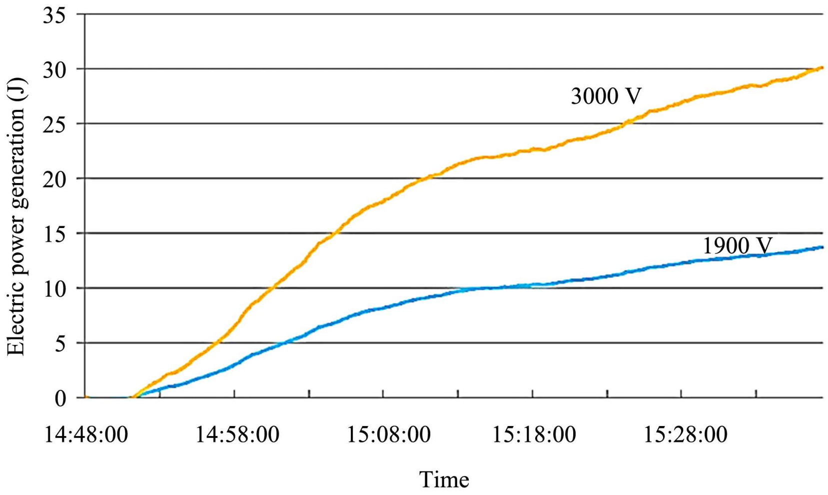


Figure 2. Total energy generation during 50 mins with bias voltage of 1900 V and 3000 V.

renewable energy generate only a small amount of generated energy and cannot always obtain generated energy, so it is necessary to store and use any generated energy.

In the case of small DEG devices, the output voltage is as high as several hundred to several thousand volts, so it is necessary to step down the output voltage in order to charge the secondary battery. However, general step-down circuits cannot handle high-voltage, intermittent output of electrical energy. As a way to overcome this, a step-down/accumulator circuit using multiple high-voltage capacitors is effective [25]. **Figure 3** is a block diagram of a secondary battery charging circuit developed for small DEG devices.

The circuit used here converts the approximately 3000 V high voltage output from the DEG into a few volts with a step-down circuit using multiple high-voltage capacitors, and stores the primary power. The energy harvesting IC monitors the voltage of the electrical energy stored in the high-voltage capacitor, and when it reaches 3.3 V, the output control switch turns ON and 3.3 V is output to the outside. This makes it possible to convert the high-voltage intermittent electrical energy from the DEG into a stable 3.3 V voltage and supply it to other secondary batteries and sensor systems. **Figure 4** shows the prototype DEG unit and charging circuit for small DEG. The DEG unit is a short cylindrical device shown in the lower part of **Figure 4**. It consists of a cartridge consisting of two stacked diaphragm-type DEs with a diameter of 8 cm and an acrylic rod that pushes the DEs to generate electricity.

First, push the acrylic rod of the DEG unit about 15 mm, and then drive it continually about 20 to 30 times to obtain a stable voltage of 3.3 V. Furthermore, by increasing the capacitance of the storage capacitor in the charging circuit, it is possible to supply current up to 100 mA [25].

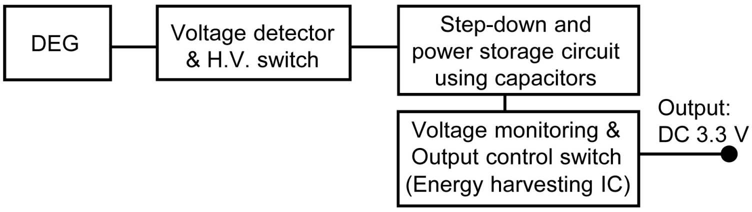


Figure 3. Block diagram of a charging circuit for a secondary battery developed for a small DEG device.

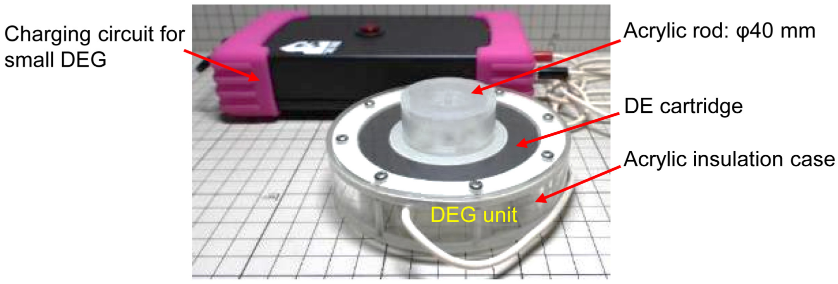


Figure 4. DEG unit and small DEG charging circuit.

Changing the elastomer material depending on the application is recommended. Specifically, times when "it is desired to generate a large force even if the extension is small", when "some degree of extension of the force is required" like in so-called muscles, and "when it is desired to drive even at a low voltage", and so forth. For example, silicon has low elasticity, but could exert a greater force under high voltage than acrylic, styrene, or urethane [36] [37]. Acrylics can achieve great elongation and force with the right choice of prestrain. In any case, since the elastomer has viscoelasticity, it depends on the pulling speed. Therefore, depending on the application, it is necessary to carefully consider the SS curve and dynamic viscoelastic characteristics when selecting the material. Silicon exhibits a relatively simple behavior due to its low viscoelasticity. In addition, when strain remains in the film formation, if it is desired to achieve elongation with less force, it is desirable to first remove the strain and then DEA. If driving with a small voltage is desired, it can be driven with a few volts if the film is made very thin [31]. In any case, if one wants to achieve a large force or elongation (or high power generation), one should use a high voltage according to the law of conservation of energy.

Next, based on Formulas (1) and (2) above, some have had the idea to mix in a highly dielectric material such as titanium barium in order to increase the output of the elastomer. However, incorporation of such materials stiffens the elastomer and reduces the elongation of DEA [38]. When generating power, the amount of power generated is reduced. In addition, a larger voltage is required to produce power or to obtain a large amount of generated power. There are some cases where a large amount of power generation, high output, or high growth cannot be expected, even if a high voltage is applied. This is because the viscoelasticity of the elastomer is affected by the type of high dielectric materials and those adjustment conditions [38].

Electrodes for DEs include metal foil, liquid metal, carbon grease, graphite particles, carbon black, and carbon nanotube (CNT). Metal foil is highly conductive, but it does not stretch much due to its hardness. It is therefore not very suitable as DEA or DEG [27]. On the other hand, while liquid metal is both stretchy and conductive, being a liquid, there is concern about leakage due to driving when it is used as a device. Carbon grease is also prone to leakage, and also has poor conductivity [38]. Carbon black is highly conductive to some extent, is easy to use as an electrode, and is inexpensive. Graphite grains are less conductive than carbon black. As a DEA or DEG, CNT is the best choice for those seeking high performance [39] [40]. In particular, single-wall CNTs have excellent electrical conductivity, but their drawbacks are high cost and difficulty in handling. Recently, however, CNT spraying has made it possible for anyone to easily create electrodes [39].

There are several methods for fabricating this electrode, depending on the materials used, the shape of the DE, the application, and the like. Here, using CNT spray, the method for manufacturing electrodes with a basic shape for a circular DEA using a CNT spray having the basic shape will be demonstrated:

The elastomer has to be masked so that when the CNT spray is applied, it is not applied to unwanted areas. A general masking tape can be used for masking. Cut out the shape of the electrode from the masking tape with a cutter or similar implement. This will be more easily accomplished if masking tape is attached to an acrylic plate or similar. A piece of masking tape cut to the shape of the electrode is applied to the surface of the elastomer. If the adhesive strength of the masking tape is too strong, it may not be able to be removed from the elastomer, so it is recommended to perform a peel test using the elastomer to be used in advance. Masking is applied to both sides of the elastomer prior to applying the CNT spray. The thickness of the electrode can be increased by overlapping the masking tape two or three times. As a guideline, the masking tape is superimposed so that the thickness is about 2 to 3 times the thickness of the electrode to be applied. Next, CNT spray is applied. Since the application method is almost the same as that of spray paints that are generally available on the market, basic handling instructions will be omitted and only the main points will be shown. The CNT spray is applied evenly with a suitable distance from the surface to be coated. If the CNT spray is too far away from the coated surface, the electrode may easily peel off, so care must be taken. The thickness of the electrode is generally about 50 to 100 μm, but since the thickness decreases slightly after drying, it is increased or decrease depending on the condition. Unlike general paint sprays, CNT spray does not apply two or three coats. This is to make the electrode a monolithic structure rather than a layered structure. Immediately after applying the CNT spray, the masking tape is removed. If too much time elapses, the masking tape and the electrodes may adhere to each other. After these operations are performed on both sides and allowed to dry completely, the electrode is completed. The key is to apply the coating quickly and accurately. Excessive application time will adversely affect the performance of the DEA, such as peeling or cracking of the electrode, and cause an increase in resistance. Another important point is to apply the CNT spray in a uniform thickness.

3.4. Increased Durability of DEs

The biggest problem with DE lifetime is its sensitivity to moisture [27] [41]. This is especially noticeable when a DE is used at high temperatures. At first, it was pointed out that the acrylic material was weak against moisture, but it turned out that silicone is also weak against moisture. However, it is known to extend life by two orders of magnitude when used at levels well below the DE's maximum performance. There is an experimental example of 10 million times even with an acrylic material [42]. Experiments have also shown that putting the DE in a moisture-resistant polymer bag to reduce pressure, filling it in with silica gel, filling it in with nitrogen, or all of these together can significantly extend life [27].

In the case of ocean power generation, the typical wave period is about 0.2 Hz, so the number of DE movements per year is about 6.3 million, and from the perspective of lifespan, practical application is in sight. From the point of view of fail-safe, it is also important to have multiple DE systems ready in case something goes wrong.

S. Chiba *et al.* succeeded in lifting a weight of 8 kg by more than 1 mm in 88 msec using only 0.15 g of acrylic elastomer [4]. The electrode material is SWCNTs. As mentioned above, by sufficiently reducing the performance of this DE, it could be used adequately for business purposes, or general use, but not for high-end use [4] [27].

Some researchers have attempted to create DEs with little or no pre-strain, with the idea that pre-strain shortens life [43]. However, inappropriate use of prestrain can lead to reduced strength of the membrane and deflection of the elastomeric membrane during actuation, which can lead to failure of the DE [27]. Similarly, if the DE is driven at a lower voltage, it is thought that its life would be extended. In order to achieve that, the thickness of the elastomer should be reduced, or the cross linkage of the elastomer should be reduced. As a result, the elongation and/or output would be considerably reduced, or the life would be even shortened. Moreover, the types of applications are limited. As mentioned above, therefore, it is considered good to drive a high performance DE with low performance.

4. Recent Application of DEs

There is usually a trade-off between the DEA's deformation amount and output [27]. Therefore, in many papers so far, miniature pumps, miniature robots (including insect robots), miniature valves, miniature switches, miniature grippers [34] [43]-[48], among others are shown. **Figure 5** shows (a) a small foot-shaped robot with three degrees of freedom, (b) a fish-shaped robot, (c) a snake-shaped robot, (d) an insect-like DEA (one that flaps its wings or jumps), (e) a gecko-shaped robot, (f) a small vibrating body, and (g) a small speaker [34] [47]. In addition, fingers, hands, arms and legs of robots have been created using a diaphragm-type DEA, or roll-type DEA made roll of sheet-type DEA (see **Figure 6**) [34] [41] [46].

Focusing on the output of DEA, G. Kovacs et al. made a diaphragm-type DEA by attaching electrodes of graphite powder to acrylic, laminated many sheets, and made it into a cylindrical shape. The cylindrical DEA was able to lift a weight of 4.5 kg [26]. However, it was driven in a suspended state (without defying gravity), and its operation speed seems to be extremely slow. As mentioned above, S. Chiba and M. Waki succeeded in lifting more than 1mm with a DEA using SWCNT electrodes on acrylic weighing only 0.15 g at a motion speed of 88 msc (see **Figure 7**). Moreover, it was lifted in a form that defies gravity. In very near future, by stacking multiple layers of this, it will be very possible to efficiently drive electric vehicles and robots that are suitable for heavy-duty work. To drive such a car, it is better to use a DE motor that can perform rotary motion instead of a linear drive. Rotational motion is achieved by superimposing a slight repulsion of the same DEA [4] [42].

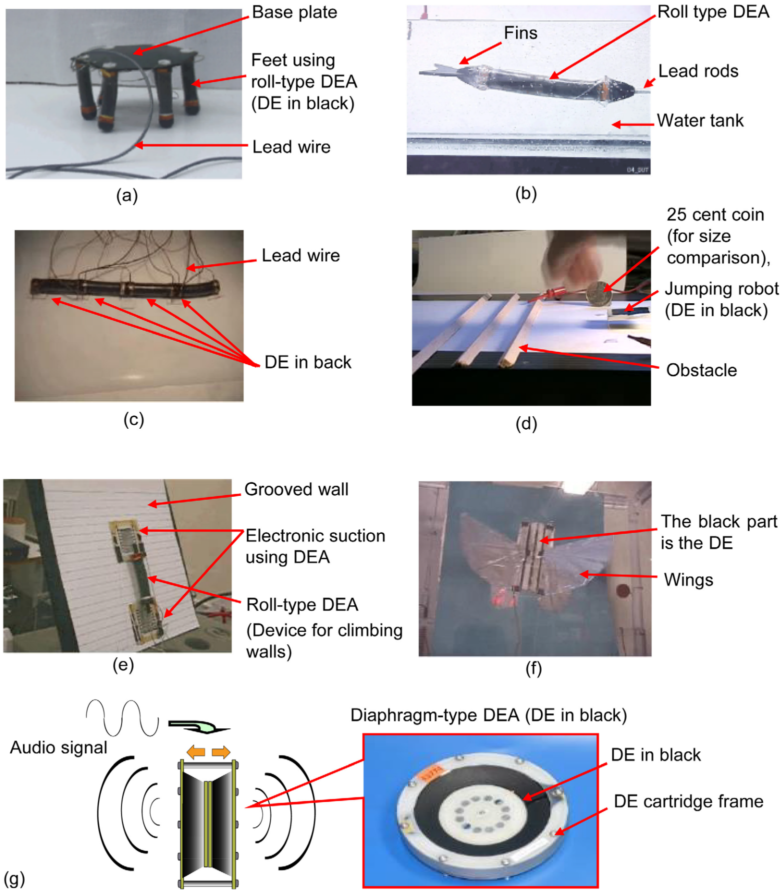
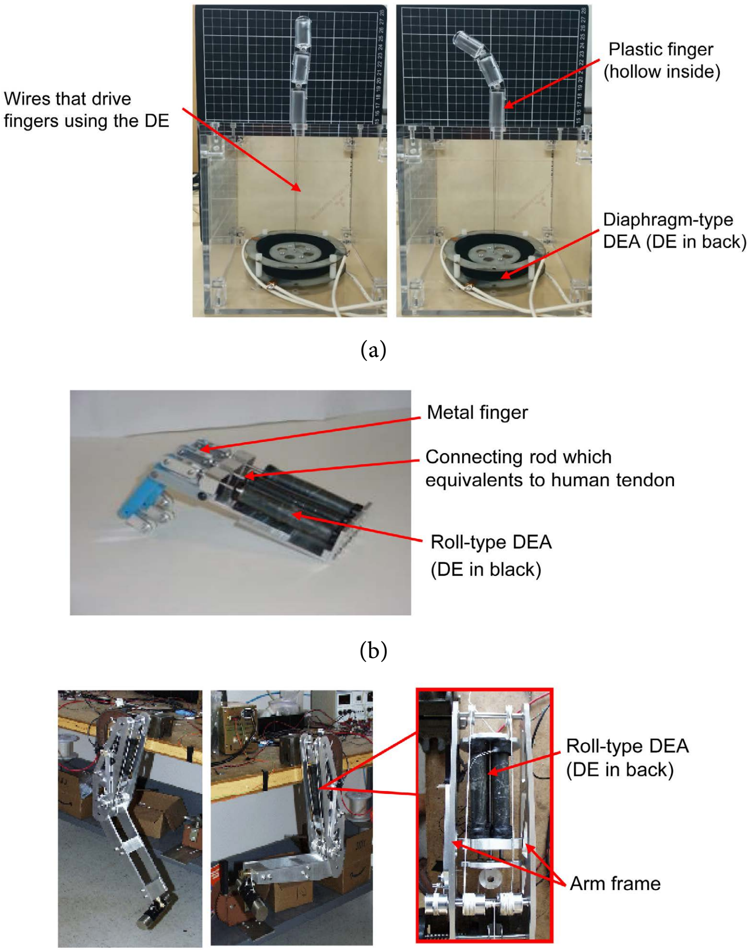


Figure 5. Small robots, speakers, etc. using DEAs: (a) Legged robot having 3 degrees of freedom; (b) Fish-shaped robot; (c) Snake-shaped robot; (d) Jumping robot that can move at high speed; (e) Electronic gecko robot equipped with a DEA sucker and DEA driver; (f) Flapping flying robot; (g) Side view of diaphragm speaker (left) and diaphragm DEA (right): This DEA can also be used as a pump or vibration element.

Next, regarding medical applications, a device has been developed to restore finger function in people who have had a stroke [44]. **Figure 8** shows a photograph of a rehabilitation glove (laminated sheet type DEA) that was developed so that the fingers can gradually move autonomously by forcibly moving the fingers repeatedly using the DEA. This type of DEA attached to the glove is not yet strong enough, but it is very much possible to make such a glove in the very near future by applying the high-power DEA shown in **Figure 7**. Another feature of this rehabilitation glove is that the layered sheet-type DEA and DES are placed above and below the finger, making it possible to measure how much the finger can bend by itself. Another medical application is a device that can help identify people who are prone to dementia and then guide them in rehabilitation [34] [44]. A sensor device with the same structure as the diaphragm-type DEA shown in **Figure 5(g)** is attached to the abdomen of multiple normal subjects and suspected dementia subjects. After that, by talking with them, the difference in the vibration of the abdomen can be seen, so discrimination/guidance becomes possible (see **Figure 9**).



(a)

(b)

(c)

Figure 6. Devices for fingers, hands, arms and legs using a DEA. (a) A model that bends and stretches the fingertip using a diaphragm-type DEA: It is the same as the principle that drives a human fingertip. Human tendons are wires, and the muscles that drive the wires are the DEA. (b) Hand model using roll-type DEA: Same as the principle that drives the human hand, metal rods (in this case, equivalent to the tendons) and roll-type GEA (equivalent to forearm muscles) enable finger flexion and extension. (c) Roll-type DEA that drives the robot arms or legs.

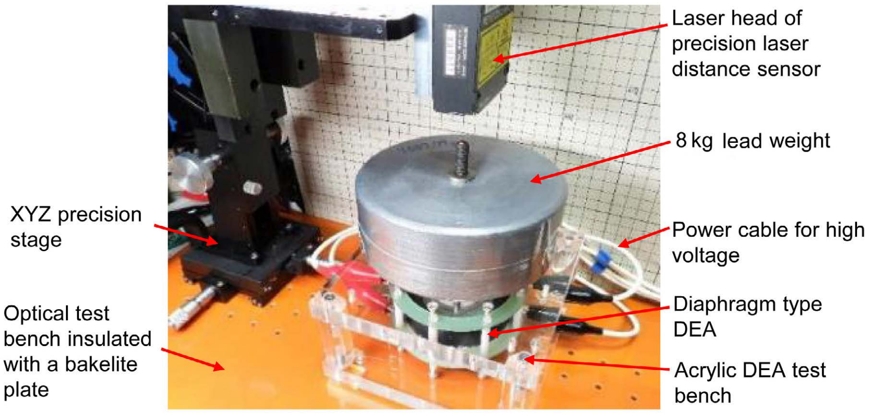


Figure 7. High-power DE.

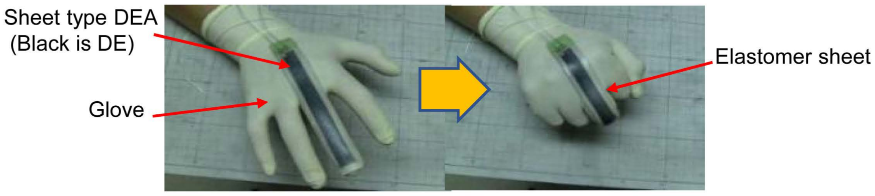


Figure 8. Rehabilitation glove.

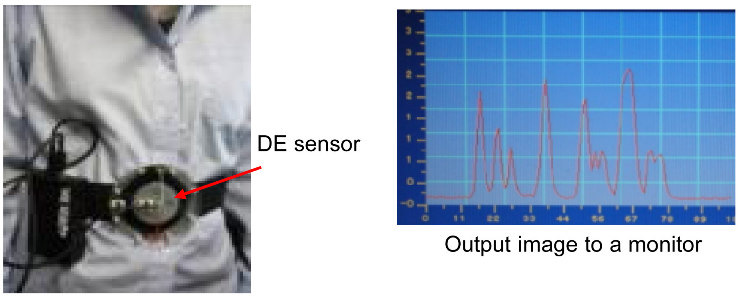


Figure 9. DE sensor that discerns dementia tendencies in people and the output images.

Similar to the DEA, the DEG is now mainly a small or medium-sized device, but using the Karman flow, a generator that can generate power even with weak wind and slight water flow has been developed (see **Figure 10**) [49]. In addition, as shown in **Figure 11**, power generation is possible even with a fairly gentle current such as that flowing along the side of a rice field. In other words, it will be possible to generate electricity without relying on conventional wind turbines or systems that drop water from a high position [27].

The power generation efficiency of photovoltaic power generation, which uses the energy of sunlight to generate power, does not increase. Currently, a type that uses light other than visible light, is being developing, but compared to other existing power generation, the efficiency is not sufficient and there are problems such as power generation costs. In addition to these, since this power generating element uses a semiconductor, it is affected by scratches on the surface, and the efficiency in the summertime is lowered. Thermal power generation systems using dielectric elastomers are also applicable to solar heating (see **Figure 12**).

In this generator, the expansion of the air inside the tube pushes the piston, and that force deforms the DEG to generate electricity. The power generation efficiency is not much different from that of solar power generation, but by using benzene and ammonia, which have a low boiling point and which expand at a lower temperature, instead of expanding air, a dramatic increase in efficiency is expected [50]. Also, even if it is cloudy, heat is transmitted, so the power generation efficiency is not expected to be so low compared to solar power generation. Moreover, it can be driven without problems even in a high temperature environment such as a desert, and of course, there is no problem even if the device surface is scratched. **Figure 13** shows an image diagram of a DE solar thermal power generator using the Stirling mechanism in the desert. It is believed that

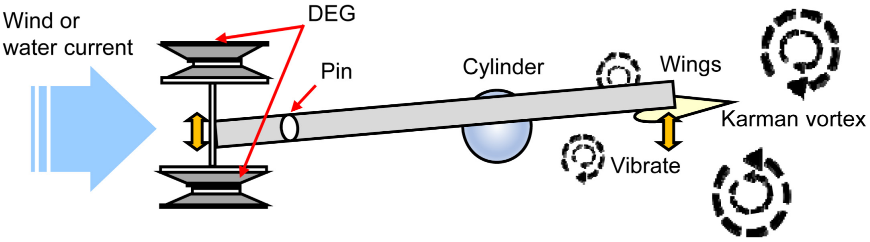


Figure 10. Fluid power generation using Karman flow.

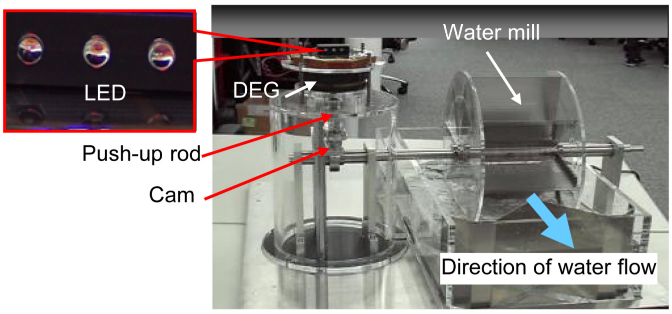


Figure 11. Water turbine power generation using DEG: A small amount of water rotates the water turbine, and the power of the push-up rods and cams deforms the DEG to generate electricity. In the system above, that electricity was used to light an LED.

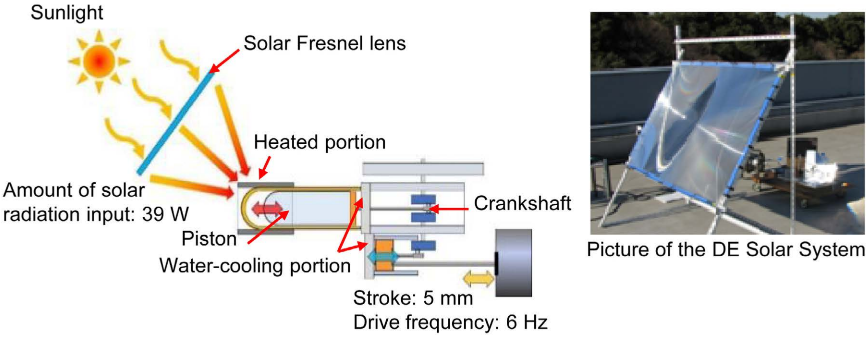


Figure 12. DE Solar thermal power Generator: a Fresnel lens having the effective size of 1000 mm × 1350 mm and thickness of 3 mm. The capacity of the tube was about 44 cm^3. The piston stroke was 24 mm, and the diameter of the piston was 25 mm. Diaphragm-type DEG having the size of 8 cm in diameter.

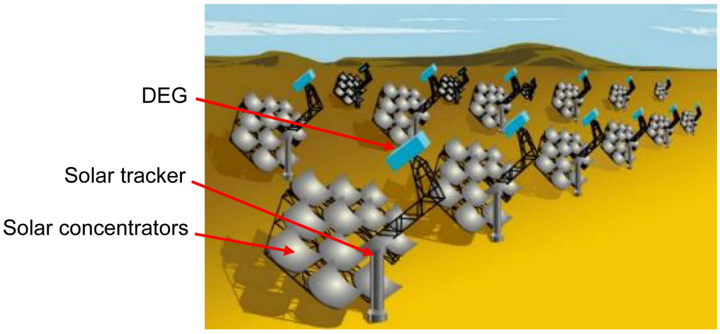


Figure 13. Image of a DE solar thermal power generation system using the Stirling system installed in the desert.

this will promote the effective use of deserts areas [27]. It is thought that by effectively consuming the heat on the surface of the desert, the temperature of the desert will drop slightly, contributing to the prevention of global warming, albeit only slightly. If a DES that can generate electricity at low temperatures is realized, it will be possible to generate electricity from waste heat of 100˚C or less, which will accelerate the effective use of waste heat [50].

Wave power generation systems have been attracting attention as renewable energy for a long time. There are still some problems, and at present, a practical system has not been completed. Recently, there are types of buoys equipped with DEGs that generate power from the height change of waves and wave currents on the sea surface. Furthermore, there are types of systems that replace existing oscillating water column (OWC) wave energy converters with DEGs [27] [51]. **Figure 14** shows photographs of a buoy-type generator equipped with DEG and a buoy-type hydrogen generator. At present, although the amount of power generated is still small, a system that approaches the efficiency of a thermal power plant is being developed by adopting a shape that conforms to hydrodynamics and by achieving the best match of elastomers and electrodes [52]. In addition, by laying sheet-type DEGs on roads, electricity could be generated from the traffic of people and vehicles. Research and development towards this end is already underway [31].

In addition to the above, there is an ocean temperature difference power generation. It is certainly possible to generate power due to the temperature difference, but it seems that it will not work well because the energy for drawing deep seawater with a pump is larger than the amount of power generation. It could be better to use DEG to generate power in case that a sufficient temperature difference is not available (in most cases it seems to be the case) and to cover the energy of the pump with DEG buoy or DEG wind power generation.

Finally, regarding the huge power generation system on the ocean, it is thought that it would be better to deploy a huge number of buoys equipped with DEGs. The buoy-type DEG generator installed near the shore connects the seabed and the DEG with a mooring wire. When waves hit the buoy, the buoy is

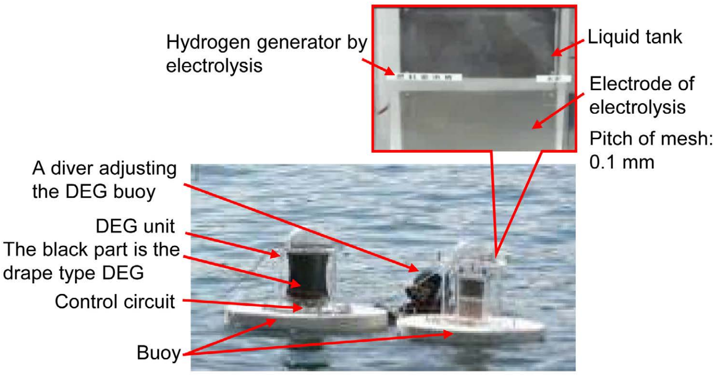


Figure 14. Buoy-type generator equipped with a DEG and buoy-type hydrogen generator.

lifted by buoyancy, and the DEG is stretched by the mooring wire to generate power. However, since such a wire cannot be installed in the middle of the Pacific Ocean, a plate was installed under the buoy, and a mechanism was created to extend the mooring wire from the difference in buoyancy between the plate and the buoy [27]. It is thought that this will enable power generation even in the deep sea. There is another problem how to transport the power obtained from this system to the mainland. In this regard, it is considered best to replace it with hydrogen once and transport it to the mainland by tanker. An experiment to convert electricity obtained from a buoy generator equipped with a DEG into hydrogen has been successful by Chiba *et al.* [52].

In addition to the various DEA and DEG functions described above, another function of the DE is the DE Sensor (DES). Also in this regard, pressure sensors [27] [53], moisture sensors [54], liquid level sensors [55] and various medical sensors [34] [44] [56] including tactile functions have been developed. The example of the medical sensor was mentioned above, but recently developed pressure sensors are small size, fairly thin, and capable of accurate measurement over a wide range [31]. As a result, the sensors that control and industrial machinery can be made smaller, which reduces their own weight and enables smarter control, which is expected to lead to energy savings [31].

To give an example of environmental monitoring of the entire local city, first, a DEG is installed between the water supply and sewerage, and electricity is obtained from the flow to check water quality and leaks, and also to manage smoke emissions from incinerators in the city. It is also possible to manage by generating electricity from exhaust heat during incineration and driving monitoring equipment.

5. Locally Global Smart Cities Based on DE Technology

Figure 15 summarizes the sites where the local DE power generation system can be installed; *i.e.*, a DE power generation system that locally produces and consumes the power obtained is shown. In addition, a super-large DE power generation system that is installed in the ocean is also shown.

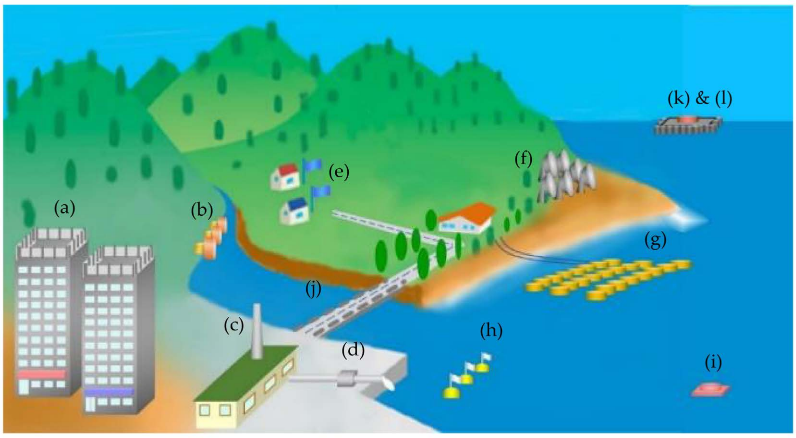


Figure 15. Example sites where DE generator systems could be installed.

1) DE power generation system in which obtained electric power is consumed locally:

a) Wind power generators on the top of buildings [49]

b) Water mill generators [50]

c) Waste energy generators [50]

d) Drain generators [50]

e) Wind power generators [50] [57]

f) Solar heat generators [34]

g) Coastal type wave generators [27] [34]

h) Water flow generators [27] [34]

i) Ocean thermal energy conversion (OTEC) systems [31]

j) Power generation on DE road surface [50]

2) Ultra large DE generation system which is installed in the ocean

k) Wave Generators in ocean [27] [34]

l) Hydrogen Production plant [34] [53] [58]

It is beneficial, if the power generation systems (a) to (j) shown in (1) of **Figure 15** are incorporated well, and the DC electrodes obtained from these can be used immediately without AC/DC conversion and with zero energy loss. In order to back up the electric power in the town where such various local DE power generation systems are installed, the electric power generated by the ultra-large Depower generation system installed in the ocean shown in (2) of **Figure 15** is converted into hydrogen and transported to town by tanker. There it can be converted back into electricity, or used directly as fuel (including fuel for cars or planes). In this way, although it is individually independent local area, it is thought that a zero-emission city and factory operation life would be possible independently based on abundant energy.

6. Summary and Conclusion

In the very near future DEGs will offer unique opportunities for both point and distributed power generation. Since renewable energy, as mentioned above, has relatively low frequency bands, DEGs seems to be a very attractive for these individual point applications. In addition, for areas which needs distributed generators, DEG clusters are considered an attractive application. DEG is still a relatively new technology, and some challenges remain in areas such as electronics, lifetime, and environmental robustness. Currently, many research institutes are actively pursuing research and development on these issues. With new power generator capabilities and new energy sources in the world being eagerly awaited, DEG technology seems to have great promise. Moreover, the DEA is extremely light and has a large output, so it is thought that it will contribute to the energy saving in various devices. There are also expectations for the existence of thin, ultra-flexible DESs with a wide measurement range that optimize their driving.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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