

Micro Robotics

Prof. Palani Iyamperumal Anand

Department of Mechanical Engineering

Indian Institute of Technology, Indore

Week 4

Lecture 18

Micro actuation and Micromanipulation - Module 03

In the earlier classes, there was a brief discussion on magnetic micro actuators for different micro-robotic-related applications. In fact, the different types of magnetic micro actuators, which include the functionality of different magnetic-based micro actuators and their suitable applications, have been discussed. Also, the previous lectures covered the different configurations of magnetic micro actuators, how they are microfabricated, and their potential applications in biomedicine. The entire spectrum of these magnetic micro-robotics is for biomedical-related applications. Okay, now we will start with piezoelectric-related actuation and a brief discussion about this piezoelectric-related topic. Some of the key fundamentals regarding piezo actuation are concerned.

So, the piezoactuation is classified into two categories. One is called the direct piezoelectric effect, and the other is called the converse piezoelectric effect. So, in the case of a direct piezoelectric effect, when a stress is applied to certain crystals, an electric moment is generated in the crystal whose magnitude is proportional to the applied stress. This effect is known as the direct piezoelectric effect.

However, in the case of the converse piezoelectric effect, when an electric field is applied to a crystal having piezoelectric properties, the shape of the crystal changes slightly. This effect is known as the converse piezoelectric effect. Ideally, with reference to a functional perspective, these direct piezoelectric effects are identified and used for sensing-related applications, and these converse piezoelectric effects are used for actuator-related applications. Based on the domain and the displacement appropriately, it can be used for either a micro level or a macro level. Whereas these piezoelectric actuators on a macro level need to integrate an appropriate stack into the system to increase the overall perspective of these piezoelectric actuators.

Now, let us see some fundamentals of these piezoelectric actuators and piezoelectricity. These piezoelectric actuators are of concern, so these piezoelectric ceramics are being used

efficiently. Consider now a piezoelectric ceramic of thickness e subjected to an electric field E . The electric field E is equal

$$E = \frac{V}{e}$$

V is the voltage created by the electrical source across the ceramic and e is the thickness. Then, this is in the case of inverse polarization, so that the ceramic is subjected to deformation induced by this effect. The expression for which is a function of the applied electric field E , which is represented in volts per meter,

$$S = E \cdot d$$

S , is the deformation produced by the piezoelectric effect. D is m/v , which is nothing but the piezoelectric deformation constant. Now, as far as these mechanical deformations are concerned, nevertheless, this deformation is not the only one undergone by the sample; other deformations must also be considered, which are due to various mechanical forces. When these are induced, an expression for the total deformation undergone by the sample is

$$S = d \cdot E + s \cdot T$$

The capital S corresponds to the total deformation, d corresponds to $D \cdot E$ plus $s \cdot T$, where s is the elastic compliance, the inverse of Young's modulus of the ceramics, and capital T is the stress resulting from an external force on the sample. Let's consider the electrical displacement, the piezoelectric materials are dielectrics; because of this, there is a displacement of electric charge, which is known as the charge density in the dielectric whenever it is exposed to an electric field. In the case of a sample, the expression for the electric displacement in the sample is

$$D = \epsilon \cdot E$$

Epsilon is nothing but the dielectric permittivity of the ceramic in the order of 10^{-9} to 10^{-2} .

The piezoelectric material would be subjected to an external force, thus generating an electrical displacement through the direct piezoelectric effect, whose expression is proportional to the applied stress T . Therefore,

$$D = d \cdot T$$

D is measured in C per N or V per m². Therefore, the expression for the total electrical displacement in the piezoelectric material is D equals epsilon E plus D dot T

$$D = \epsilon \cdot E + d \cdot T$$

We can write S and T in matrix form such that

$$\begin{pmatrix} S \\ D \end{pmatrix} = \begin{pmatrix} s & d \\ d & \epsilon \end{pmatrix} = \begin{pmatrix} T \\ E \end{pmatrix}$$

If D equals 0, there is no coupling between the electrical and the mechanical domains.

So, an expression for deformation and electric charge displacement would be found for an arbitrary material. This coefficient D is therefore defined as the piezoelectric character of a material, in particular the strength of the electromechanical coupling within it. So, the larger D , the stronger the coupling. The piezoelectric ceramics are three-dimensional. Therefore, they need two pieces of information to describe each vector.

The phase to which the factor is applied and its direction is

$V = V_{ij}$, i is the phase of the vector, and j is the direction of the vector.

So, the symmetric condition on the stress in a material implies $v_{\{ij\}} = v_{\{ji\}}$. So, for simplification of notation for symmetric conditions, this is a kind of notation in generalized form, which is available, and the overall equation, the generalized 3D space equation, is represented in the following form. Now, constitutive equations are a kind of generalized equations or generalized parameters that we consider with reference to general piezoelectric structures. However, let's consider a constitutive equation of piezoelectric actuation, so we have a strain S_{ij} , which is represented as $d_{kij} e_k$ plus this equation, and the electric field is represented as D_i , where S_{ij} is the strain sensor, E_{ij} is the elasticity, E_{jk} is the dielectric tensor, T_{kl} is the stress sensor, and D_{ikl} is the piezoelectric tensor.

Strain : $S_{ij} = d_{kij}E_k + s_{ijkl}^E T_{kl}$

Electrical Field : $D_i = \varepsilon_{ik}^T E_k + d_{ikl} T_{kl}$

This generalization is concerned; let us consider two special cases of the system. One is a kind of short circuit case where the electric field applied to the piezoelectric material is zero. Then rewrite the expressions for S and D as shown in this equation.

$$S = sT$$

$$D = dT$$

However, in the case of an open circuit, the displacement of electric charge is zero. It can be rewritten as the expressions of S and D, which are represented over here.

$$0 = \varepsilon \cdot E + d \cdot T \Rightarrow E = -\varepsilon^{-1} dT$$

$$S = d \cdot E + s \cdot T \Rightarrow S = (s - d^T \varepsilon^{-1} d)T$$

The difference between the elastic compliances in the short circuit case, which will be written in the open circuit, can be written as S^E .

$$s^E = s$$

$$s^D = (s - d^T \varepsilon^{-1} d)$$

The short circuit case is S^E , and the open circuit case is S^D . Thus, it can be concluded that the strength of the electromechanical coupling depends in practice on the value d. Therefore, it can be represented in general form.

$$S = s^E T + d^T E$$

$$D = dT + \varepsilon^T E$$

As far as this piezoelectric actuation is concerned, the concept of poling will be involved. This polling process is an essential step in piezo manufacturing. It is important to understand the principle as it conditions the material's behavior. It helps tune the material based on requirements or the overall functionality. The PZT is a ceramic formed of multiple

domains before poling; the domains that define a local polarization are randomly oriented, and the overall average polarization of the material is zero. Before the polling, the domains were not aligned.

However, after the polling, these domains were aligned. After removal, the polarizations are in tension, which is helpful for appropriate applications and for molding it with reference to the functional characteristics. During the polling process, a high voltage typically in the order of 0.1 to 1 kilowatt per mm is applied to the material at a temperature close to the Curie temperature, where the ferro-paraelectric transition is observed. The strong electric field and the heat applied to the material cause a reorientation of the domain towards the direction of the electric field.

A maximum net polarization is then obtained from the crystal. Upon cooling, the thermal relaxation process induces a diminution of the crystal, which will result in the net polarization. These are some of the different steps involved in the polarization activity. As far as a strain response as a function of applied voltage is concerned, the butterfly curve is considered to be one of the key characteristics to investigate and quantify the piezoelectric domain. In order to quantify this piezoelectric structure, ideally, the plot is oriented between the strain and the voltage. So, in order to examine the behaviour of a piezoelectric material submitted to an electric field, it is assumed that the electric field is aligned along the polarization direction and examines the evolution of the strain upon the modulation of the voltage. After the polling process, domains are oriented along a preferred axis. Point A on the curve lowers the voltage down to point B, a pseudo-linear regain that corresponds to the piezoelectric strain response of the applied field. Now, once the voltage is further lowered and becomes negative, the strain follows the direction of an applied electric field until point C, where the domain starts to reorient in the electric field. When it switches to point D, where domains are fully reoriented in the direction of the applied field.

If we increase the voltage again up to positive values, we find a symmetric behavior that is called a butterfly curve. Now one of the major issues with reference to piezoelectric structures is that these piezoelectric actuators exhibit a kind of non-linear behavior, and their characteristics exhibit hysteresis. To plot a curve with reference to displacement and voltage, it can be easily observed that there is a kind of characteristic that exhibits hysteresis in the particular process. This hysteresis will have a defect that will try to impact the overall performance of the usage of these piezoelectric structures for different functional applications. To overcome this, one of the important aspects is the addition of a supporting layer, like the ones we discussed regarding the unimorph and bimorph concepts.

So these unimorphs and bimorphs are well integrated with these piezoelectric structures, so that, appropriately, hysteresis can be considerably reduced, overcoming the overall hysteresis, and they can be used functionally for different applications. Next, the

piezoelectric actuation with reference to creeping behavior indicates that if a constant voltage is applied to the material, the strain tends to drift over time, and the empirical law used to capture the drifting effect is shown here.

$$\Delta L(t) = \Delta L(t_0) \left[1 + \gamma \ln \left(\frac{t}{t_0} \right) \right]$$

The key parameters involved in these drifting effects are that a constant voltage is applied to the actuator, leading to an elongation of ΔL . The time-dependent drifting is captured by a logarithmic law that describes the behavior of the material after a certain time t_0 , and typical values for γ are 0.1 seconds and a fitting constant γ between 0.01 and 0.02. To observe the overall plots, the plot is with respect to elongation and time t ; thus, this is a kind of material response. However, this is a kind of desired behavior that is observed experimentally. So, the deviation is denoted as $t = t_0$. So, the motion amplitude of a bulk piezoelectric actuator remains small. For instance, for the normal mode, the value of d for the best piezoelectric material is in the range of 3.75 times 10^{-10} m/V.

Using the constitutive equation, the corresponding deformation is a function of the tension U applied to the material and the electrode thickness h .

$$S = d \left(\frac{U}{h} \right)$$

So, this is a kind of quantified equation that basically discusses the function of tension. For a 1 mm thick material driven at 100 volts, the normal strain will therefore be S equals 3.75 into 10^{-5} %, which corresponds to a relative elongation of a few tenths of a nanometer. Now, it needs to discuss the amplification principles that are used for piezo actuators. Upon closely observing the amplification principles, there are electrodes that are available and the piezoelectric ceramics. This is a kind of interdigitated structure. The first idea to significantly amplify the motion amplitude is to stack up several actuating layers. With that, the motion amplitude is multiplied by the number of stacks.

A common configuration is to use a structure with interdigitated electrodes. This configuration offers the advantage of amplifying the motion without increasing the applied voltage. There are a wide variety of these piezoelectric structures. In fact, these piezoelectric structures are efficiently deployed for different applications, which include a kind of micro grippers, micro actuators, and micro energy harvesters. Even in several cases, it is also used for a kind of micro-manipulation system that is being deployed. Now, let us see some of the applications of these piezoelectric actuators and how they are deployed for

different applications. These piezoelectric systems are well known for pump applications. In fact, a wide variety of piezoelectric-based pumps are being deployed for different functional applications. This is one such pump where the piezoelectric-driven micro-membrane pump consists of two glass plates and a silicon disc, which is sandwiched between these two plates. The silicon disc is a structure made by etching and contains a pump chamber as well as a suction valve and a discharge valve.

The upper glass plate serves as a pressure-sensitive membrane. It can change the volume of the chamber with the help of a bonded piezo disc, which is nothing more than an actuator. In this particular case, there is a piezo actuator in place, a suction valve, and a discharge valve. Through the suction valve, there is an inlet to the system, and then through the discharge valve, the outlet of the system can be observed. There is a pumping chamber, and then there is a microstructured silicon disc. This microstructured silicon disc will act as a support structure when the piezo actuator actuates, and it is used for the suction mechanism. When the voltage is applied, the membrane buckles downward and the liquid is forced out through the discharge valve. When the voltage is removed, the membrane returns to its original position and the pump sucks in the liquid through the suction valve. The diameter of the macro prototype of this pump is around 75 mm, and the thickness is around 2 mm.

The discharge pressure is 0.2 bar with a maximum of 0.5 bar, and the pump has an operating voltage of 300 volts at a flow rate of 0.6 milliliters per minute. The micropump is able to close very precisely within a displacement stroke of 0.2 microliters. These kinds of pumps are used efficiently for micro lubrications. Sometimes it is also used for biomedical-related applications. Next, let us talk about a microvalve. As far as a microvalve is concerned, a microvalve may have a problem when the external pressure is much higher than the internal pressure. So, acting on the wall, it can no longer be opened after it has been closed.

One solution is the use of a powerful microactuator, which can overcome external pressure. This is a kind of system that shows a piezoelectric micro wall with a schematic. The wall is constructed on a glass substrate. A wall membrane is made of silicon using the etching technique, and it is mounted on the glass substrate by an anodic body. The actuator system consists of a glass membrane and a piezo-ceramic disc. In this case, it has a bottom glass and an actuator membrane glass on the top. Then there is a piece of ceramic disc that is available. These microstructured wall membranes are silicon, and then there is a wall seat arrangement. With reference to this actuation, the overall displacement of this wall is seated. The wall membrane and the actuator membrane relate to the prism-like connecting element.

The micro wall opens and closes when the actuator and the wall membranes simultaneously lift or release with the help of a piezoelectric element. The wall prototype has a 130-micrometer-thick actuator membrane with an inner diameter of 10 mm, and the piezo disc acting as an actuator has a thickness of 300 micrometers. When a voltage of 50 volts is applied, a gap of 4 micrometers can be reached. These microvolts have potential applications in drug delivery and automotive-related applications. Now, let's introduce one of the important application areas where these piezoelectric systems are efficiently used for micro-manipulation applications.

In this particular aspect, let's discuss the concept of the chopstick gripper. The overall construction of the chopstick gripper includes a part of a robotic arm stub. Then there are two fixed base plates, and a piezoelectric actuator in the form of a Stewart platform, which is a kind of parallel manipulator, is placed on both sides. Then there is an end effector, which is a kind of chopstick, used for micromanipulating micro materials or for the micromanipulation of small-featured structures, etc. The very important application area of this piezoelectric actuator is the fine manipulation and adjustment of microobjects.

Piezo actuators can precisely position these objects with an accuracy of 10 nanometers. The development of a piezoelectric micro hand for micromanipulation of tiny objects has been pursued by several research groups for several years. This is one such configuration. The main configuration of this is two piezo-driven chopstick-like fingers, each having six degrees of freedom, designed to manipulate the micro-object like a human hand. The two-finger design was specially conceived to work in the micro world where gravity and the moment of inertia play only a very minor role.

Therefore, two fingers are sufficient for manipulating the micro-objects in this system. This has a different orientation, and this has a different orientation. Appropriately, these chopsticks are used efficiently for micromanipulation. Now, in addition to this, piezoelectric structures are also efficiently used for optical scanning, especially in areas where mirror-based micromanipulations or micro-opto-microtronics-based micromanipulations are employed. Such systems are efficiently used. In this particular aspect, a laser scanner integrated with a piezoelectric actuator has potential applications in different fields. In this particular case, there is a central rod, and then there is a piezo actuator. Then there is a mirror deflection plate, a diaphragm, a workpiece, and a laser that is there. By these adjustment screws, the piezo actuators move back and forth, resulting in high frequency. These high frequencies can deflect the mirrors based on the required system.

By adjusting the screws, it aims to limit the overall position. By limiting the position and

appropriate orientation of these screws, one can manipulate the laser beam. Here, a laser beam is coming, and the overall force is being transferred to a diaphragm. There is a delicate diaphragm, and there is a mirror that is available. The laser scanner hits the mirror, and then by adjusting the screws, the overall system is kept in tension, and a piezo actuator is used for high-frequency manipulation.

Basically, a high-frequency actuation allows for a significant amount of displacement. This displacement is the workpiece, and it can be used to study the optical receiver's capability. This is one configuration with reference to the laser scanner. The other configuration is a kind of piezoelectric-based micromanipulation. In this piezoelectric-based micromanipulation, a piezoelectric element is used as an actuation mechanism, especially for the movement of the surface.

Here, on this particular surface, there is a kind of ground, a frame body, and then there is a piezoelectric beam that exists. The piezoelectric beam is made to vibrate at a very high frequency. When this vibrates at a very high frequency, the vibration is transferred to the frame body, and from the frame body, it is transferred to the traveling wave. When it is vibrating at a very high frequency, this vibration, since it is translated to the traveling wave appropriately, can result in a kind of displacement being observed. Of course, the system will start moving in a forward direction to get a particular reach. In this particular case, this is a kind of proven technology. In this proven technology, it is efficiently used for carrying certain amounts of payloads. Since it has a vibration in place, it causes its own disturbance. However, from a manipulation perspective, this is a kind of efficient structure that is employed. Now, this system has a kind of a configuration.

In this configuration, let us consider that there are two beams. This is a kind of side view. It has a single beam, and this beam is going to vibrate, and then it is going to disperse the overall motion of the system. It has two beam structures; one beam is vibrating at a very high frequency, and the other beam is vibrating at a lower frequency. One that is vibrating at a very high frequency will try to create movement in this direction, and one that is vibrating at a very low frequency will be the axis point for the rotation. In fact, when this beam is ideal, it will act as an axis point. When the other beam is vibrating at a high frequency, there will be a kind of deflection that exists. Similarly, if rotation is needed in this direction, it will vibrate at a very high frequency, and it will be in a standstill position so that this standstill position is capable enough of creating a different orientation. In case a straight movement is required, the vibration should occur at a high frequency in a forward stroke so that it can sense the vibration or convert this vibration to create a displacement in the forward stroke. In the case of a backward movement, it needs to have a reverse frequency so that a kind of lift can be generated.

This lift is capable enough to move the system in a backward movement. Similarly, this is a kind of configuration where a piezoelectric beam is used. In certain cases, these

piezoelectric beams can be replaced with piezoelectric-based unimorph or bimorph structures. Now, let us consider if I have a piezoelectric beam. In this piezoelectric beam, there is a kind of structure that is established here. This structure is a type of robotic platform. Over this robot platform, there is a piezoelectric structure in the form of a piezo leg, and there is a smooth surface that exhibits. Instead of the vibration, it is going to be a single step that is going to be exerted on the surface. So seeing this single step will be completely like this. This single step will create a stick, and then it will create a slip. This stick-and-slip sequence will result in a kind of positive displacement over the surface.

When there is a platform moment, it is there. There is a kind of stick-slip that exhibits which will result in a kind of micromanipulation of the thing. In fact, the distance between this stick and the slip will have control over the micromanipulation or the micron displacement exerted on this particular system. This is called a stick-stiff-based actuation. There is going to be a kind of sliding force that exists, and this sliding force is a kind of ploughing effect or a sliding force effect that is exerted, and this sliding force exerted will result in a kind of movement in the system. Now, apart from this, there is the extension of such a system known as the scratch drive arrangement. In this scratch drive arrangement, it is concerned whether I have a piezoelectric structure and if this piezoelectric structure vibrates at this particular frequency, this can be helpful for the movement of these scratch drive structures in a positive direction. When the vibration occurs, you can have forward motion. When the vibration is against the drag force, towards the lift force, there will be a kind of reverse motion that it can exit. In order to encash this micro-manipulation process, it needs to either encash the frequency or the displacement. In this particular configuration, lets encasing the frequency to generate the appropriate displacement.

Here in this particular case, we are encashing the displacement to get a appropriate manipulation. For fine and precise manipulation, this is used for large area propulsion; for longer propulsion, such a configuration was used. So overall, this module discussed the configuration of a piezoelectric actuator, the direct piezoelectric effect, and the converse piezoelectric effect. It also discussed the various parameters that affect the piezoelectric capability, one of which is a kind of mechanical deformation. Then, it covered the electrical displacement that it exhibits. Then, about the overall representation of these piezoelectric structures in the 3D space environment. In fact, I have not gone into the details of the complete derivation of it. This is just for understanding. However, when you try to apply it, it is more of an experimental node.

And then, from a design perspective, it will cover its structural design. And then from the perspective of the constitutive equation, it covered the different parameters that influence the constitutive equation, which include the strain tensor, elasticity, the dielectric tensor, the stress tensor, etc. Then it covers the generalization of 3D space. It considered two cases: one is a kind of short circuit case, and the other is an open circuit case. It also covered how piezoelectric polling is done, how polling will have an impact on the functional

applications, and how the response of the piezoelectric structures is basically quantified through the butterfly curve.

This type of butterfly curve is being exerted. Hysteresis is considered to be one of the major drawbacks of piezoelectric structures. Also, it covers the creeping behavior and how an amplification factor has an impact. Then, we have seen two or three configurations: one is a kind of micro membrane pump, piezoelectric-based, and a micro wall that is available. So a chopstick gripper, which is conventionally available, piezoelectric-based grippers, which are used for kind of micro-manipulating the systems, and then how the micro actuators are used in the laser scanner.

Some of the configurations of these piezoelectric-based micro-manipulations. How it is being deployed for where it has encased the vibration and the displacement based on the requirement as well as the characteristics. The next module will discuss the electrostatic actuators.