Microrobotics

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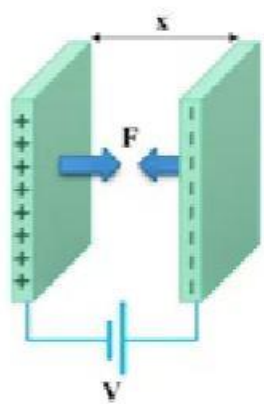
Week- 04

Lecture No- 19

Micro actuation and Micromanipulation - Module 04

We have discussed magnetic-based and piezoelectric-based actuators in this module. Now we will discuss electrostatic-based actuators. For the electrostatic-based micro actuators, the basic principle is the generation of electrostatic force by applying a voltage across the two capacitor plates that are separated by an insulator, such as an air gap. Thereby, opposite charges are formed on the plate, and this potential results in an attractive force between the two electrodes. So, the ability of the electrostatic actuator to generate voltage at very high frequencies, along with the very low inertia of the moving part of an actuator on a micrometer scale, allows for rapid operations. The basic principle underlying an electrostatic actuator is Coulomb's law acting between two electrically charged bodies, which produces mechanical work and, consequently, in the case of an actuator, a motion that is controlled using the voltage between the two bodies.



Fundamentally, an elementary electrostatic micro actuator consists of two planar electrodes across which a voltage U is applied. It therefore acts as a capacitor. The force F acting between the electrodes of such a system can be determined from the electrical energy We stored in the capacitor and is given as,

$$F = -\nabla W_e$$

If we write the capacitance as C, then We can be expressed in the following manner:

$$W_e = \frac{1}{2} C U^2$$

To calculate the motor force of the electrostatic Microactuators, we need to calculate the value of t and F to understand the behavior. In the mentioned equations, the W_e depends on this U^2, and the same is true for F. Its direction is therefore independent of the sign of U (in either case, the forces are attractive). So, we assume that two electrodes, each with an area A, are parallel and perfectly flat. Under these conditions, if *x* is the distance between the two electrodes, the capacitance is given as,

$$C = \varepsilon \frac{A}{x}$$

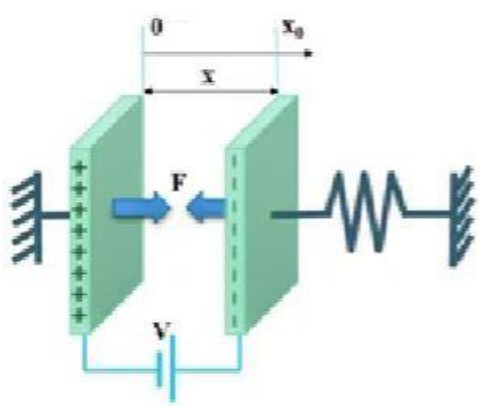
So, ε is the dielectric permittivity of the medium. Also,

$$W_e = \frac{\varepsilon A}{2x} U^2$$

So, the vector force F acting along the x-axis is,

$$F = \frac{\partial W_e}{\partial x} = \frac{\varepsilon A}{2x^2} U^2$$

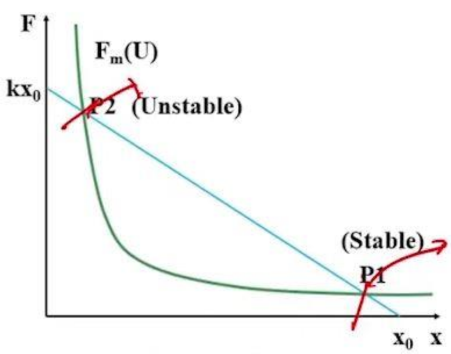
Therefore, an attraction acts between the two plates of the capacitor driven by the voltage U and increases rapidly as *x* decreases. Since microsystems are generally deformable, an electrostatic micro actuator is normally used in the manner shown.



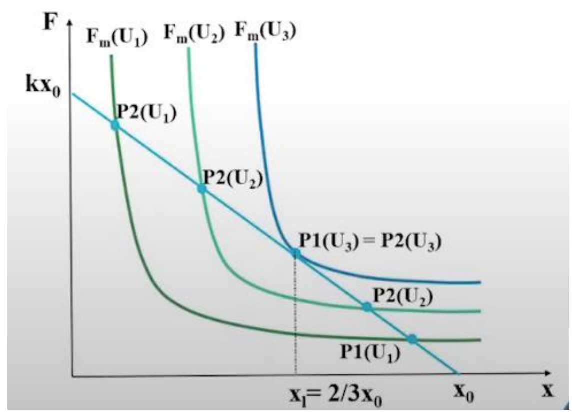
So in this case, the positive charge is fixed, and the negative charge is connected to a spring-like structure. This is an electro-micro actuator acting on a deformable elastic structure. The rest position at U = 0 of the mobile electrodes is $x = x_0$. In this case, vertical actuators with a parallel plate's configuration are considered. Here, the motor force F_m of the actuator and the resistance force F_r are associated with the stiffness k of the structure being pulled by the mobile electrode and are given as,

$$F_m = U^2 \qquad \text{and} \qquad F_r = k\,(x_o - x)$$

In equilibrium, these two forces must be equal: $F_r = F_m$. Given their dependence on x, these forces can be varied, and the influence of these forces can be studied through the given figures.



Plot of F_r *and* F_m for fixed U



Plot of F_r and F_m as U increases

The plot of F_r and F_m for the fixed U is shown, which suggests F_m reduces with increasing x. However, when we see the characteristics with increasing U, the behavior is the same, but the value of F_m is less for the same value of x. Also, with increasing U, the separation between the two equilibrium states reduces.

For the vertical actuator with the parallel plate, there are two equilibrium points P_1 and P_2. P_1 corresponds to the stable equilibrium point, and P_2 corresponds to the unstable equilibrium point. Beyond the position of P_2, the mobile electrode sticks to the fixed electrode. In such cases, to avoid a short circuit, it is useful to deposit a very thin insulating layer on the electrodes. The limit for the use of such an actuator is then defined by the case where, as U increases, a situation is reached where P_1=P_2.

The available controllable range of the actuator is therefore x_o, x_1. For the calculation of x_1, the following systems need to be solved,

$$F_m(x_l) = F_r(x_l) \qquad \text{(Forces equal)}$$

$$\frac{dF_m}{dx}(x_l) = \frac{dF_r}{dx}(x_l) \qquad \text{(Gradient Equal)}$$

where we are considering one as a force that is equal and the other as a gradient that exists equally. It can be easily shown that $x_1 = \frac{2}{3}x_o$, which then gives a controllable range of (x_o - x_1) of the actuator as x_o/3. This result is remarkable, and it is independent of the actuator and the stiffness of the structure on which it is acting.

Now, let us consider that the voltage driving the actuator can be varied between 0, corresponding to the position x_o of the mobile electrode, and U_1, corresponding to the position x_1 of the mobile electrode. Equating F_r and F_m gives us the fundamental equation for voltage as,

$$U_l = \sqrt{\frac{8kx_0^3}{27\varepsilon A}}$$

This voltage is called the pull-in voltage. This pull-in voltage plays a vital role in the actuation of the structures that work on the electrostatic behavior. This can also be referred to as $U_{pull-in}$.

Consider the example of a capacitor in a vacuum whose electrode area is 100 × 100 μm^2 with an initial intra-electrode gap of x = 3 μm that is acting on the microstructure of stiffness k = 2 N/m, which corresponds to the stiffness of a cantilever made of silicon with dimensions 500 × 50 × 5 μm^3. The travel of the actuator is 1 μm for a voltage between 0 and $U_{pull-in}$ = 13.4 V.

This will give clarity on what the operating voltage will be and how much displacement is expected when an operating voltage is applied to this particular system. Now, when the pull-in voltage is reached, the mobile electrode is brought into contact with a fixed electrode, (or rather, it is separated by the thickness of the insulating layer). So, in this situation, we treat the thickness $t_i$of the insulator as negligible compared to x_o, and the attractive force is given as,

$$F = k\ (x_o -\ t_i) \approx kx_o$$

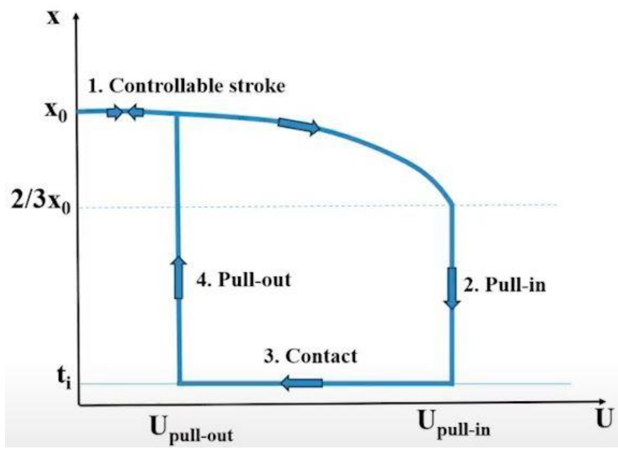
If the voltage is reduced to below $U_{pull-in}$, then F_m can be reduced until the situation where $F_m < F_r$ is reached. If we assume the pull-off force, the adhesive force between the two electrodes is negligible; this will result in the separation of the mobile and fixed electrodes.

The threshold voltage that produces this separation, known as the pullout voltage ($U_{pull-out}$), is such that,

$$F_m = \frac{\varepsilon A}{2t_i^2} U_{pull-out}^2$$

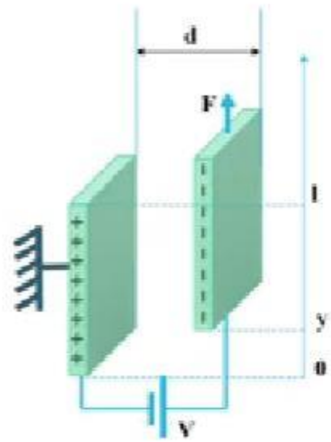
Then, $U_{pull-out} = \sqrt{\frac{2kx_o t_i^2}{\varepsilon A}}$

The overall performance of such a kind of electrostatic actuator can be studied with a plot of graph separation (X) versus voltage (U).



Initially, a controllable stroke can be executed up to the supply of $U_{pull-in}$ voltage. Then there is a sudden dip in the separation (X) because contact has been established between the electrodes. When the voltage is reduced to pull-out voltage, the electrodes separate again. This cycle will continue for the entire actuation process.

Returning to the same example used earlier and considering the insulating layer that is 100 nm thick, we can observe that $U_{pull-out}$ = 1.16V. Under these conditions, the full range of travel of the mobile electrode can be represented in terms of a hysteresis curve as shown above. This diagram shows the controllable range but also shows that it is possible to control the actuator in an all-or-nothing manner by driving the pull-in and pull-out cycle of the actuator. This principle is, for example, used in a scratch drive actuator.



Now, let us consider one more configuration that is a lateral actuator with parallel plates. This actuator consists of two parallel plate electrodes. The mobile electrode undergoes a lateral displacement with no vertical travel permitted. In this case, under the condition -1 < y < 1, in order to ensure there is always some overlap between the electrodes, the capacitance of the effective capacitor produced and the stored electrical energy are respectively,

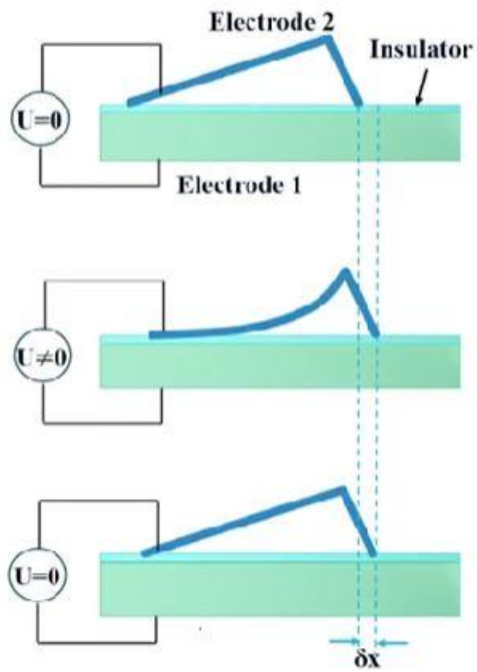
$$C = \frac{\in(l-y)p}{d}, \quad W_e = \frac{\in(l-y)p}{2d}U^2$$

The force vector F produced has a strength that is represented by the following equation

$$F = \frac{\partial W_e}{\partial y} = \frac{\in p}{2d}U^2$$

It can be seen that this force is independent of the current lateral position y of the mobile electrode. If U is constant, this force remains fairly constant throughout the travel of the actuator. Consequently, the stability considerations that apply to the vertical actuator are not relevant here. As in the case of a vertical actuator, the force produced is an attractive one. For the lateral actuator, this maximization of the capacitance will tend to draw the two electrodes on top of each other. This principle of maximization of capacitance can be used as a simple and intuitive way to understand the motion of an electrostatic actuator. If y changes sign, the driving force also changes sign. Thus, the actuator works in both directions of the displacement of the mobile electrode. These were some kinds of configurations that show the overall working capability and functionality of the electrostatic actuators.

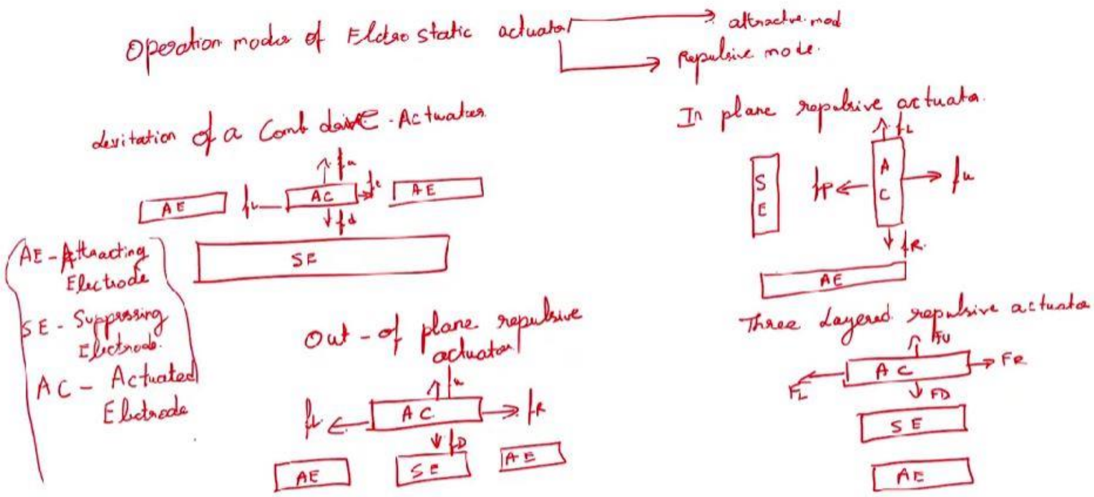
Now let us see some of the electrostatic actuators that are being used for micro robotic applications.



This actuator is called a scratch drive actuator. The figure shows the overall configuration of an electrostatic scratch drive actuator, which has an insulator placed between two electrodes. Electrical biasing is applied in order to generate the electrostatic charge in this actuator. These scratch drive actuators were proposed by Akiyama and Shono in 1993. In this actuator, one of the electrodes is formed from a flexible plate and a foot. The two electrodes are separated by a thin insulating layer. The whole micromachined structure is commonly made of polysilicon. When a voltage is applied between the two electrodes, the attractive force field produced between them implies that if it is large enough, part of the flexible electrode will stick to the other electrode, meaning the foot will slide forward.

Before going into this, let us see some configurations of the different types of electrostatic actuators that are being established for micro robotic applications. Alternatively, we can also say the different operating modes of these electrostatic actuators. The operational modes of the electrostatic actuator are classified into two: one is called the attractive mode, and the other is called the repulsive mode.

Let us consider the first configuration, which is the levitation of a comb drive actuator. The configuration is shown in the figure. The basic components are SE, AC, AE, and AE. AE is called the attracting electrode. SE is called a suppressing electrode, and AC is called an actuated electrode. Attractive force acts betwwen the electrodes which causes a displacement by decreasing the gap. The forces acting in the configuration are F_u, F_D, F_R and F_L. The actuated electrode (AC) will move between the two attracting electrodes (AE) and it will it will not have any impact on the suppressing electrode (SE). It will try to stick onto the surface of the suppressive electrode.

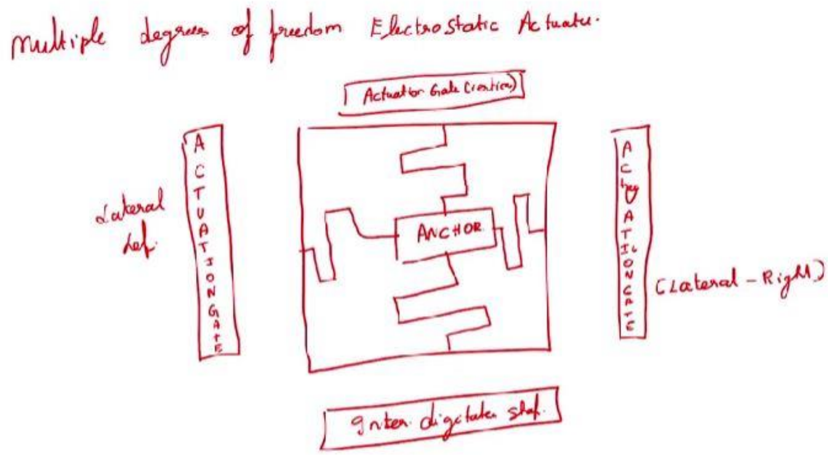


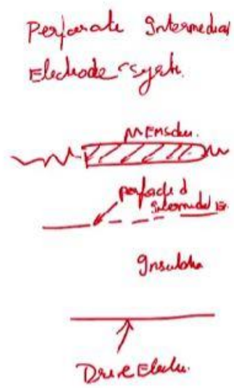
The second configuration is called as in-plane repulsive actuator. Here also we have AE, AC and SE. The forces which are exerted on AC in all the four directions are F_L, F_u, F_R and F_P.

Another configuration is called as out of plane repulsive actuator. So, the configuration is shown in the figure including AC, AE, SE and AE. So, this is a kind of configuration which is used for movement. The forces which are exerted on AC in all the four directions are F_D, F_R, F_U and F_L.

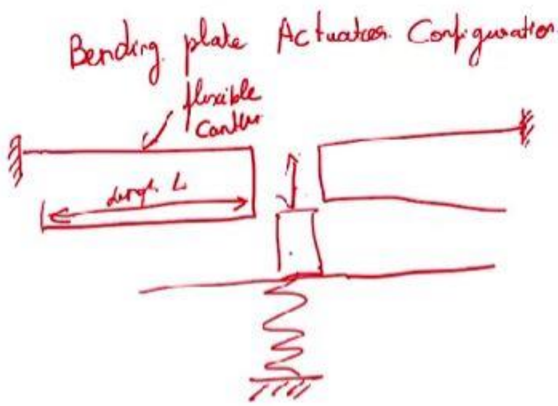
The last configuration is called as a three-layered repulsive actuator which can be represented as shown in figure. The forces acting on AC are F_R, F_L, F_U and F_T. These are the different configurations in the case of electrostatic actuator and the different electrodes which are participating in different configurations. These configurations can be deployed for different micro robotic related applications as per the requirement.

Let us see some of the types of electrostatic actuators which are being used for micro robotic applications. One we had already seen is a scratch drive. Another type can be multiple degrees of freedom electrostatic actuator. Here, we have a frame. Within the frame, there is an anchor. The anchor is connected to a serpentine kind of structure. For actuation, there is an actuation gate vertically, actuation gate lateral right and actuation gate lateral left and then there are interdigitated shafts and stationary holders. This system is mainly meant for multi-degrees of freedom so that we can use it for anchoring or manipulating the beam based on our requirement. In certain cases, we can also have a manipulating holder or needle which can be used for handling jobs.





Another configuration is called as perforated intermediate electrode-based system. It consists of a drive electrode, a perforated electrodes and insulators. On top we have MEMS device which can have an intermittent actuation as per the requirement. Apart from this, another configuration is called bending plate actuator configuration. It consists of a flexible cantilever and a rotor spring arrangement. During actuation the rotor spring arrangement reciprocates between the cantilevers as shown in the figure. Such kind of actuators are used for micro manipulation capability.



As far as electrostatic charge is concerned, comb drive actuators are widely configured and used actuators.