Microrobotics

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Microsystems for Microrobots (Manipulation) - Module 07

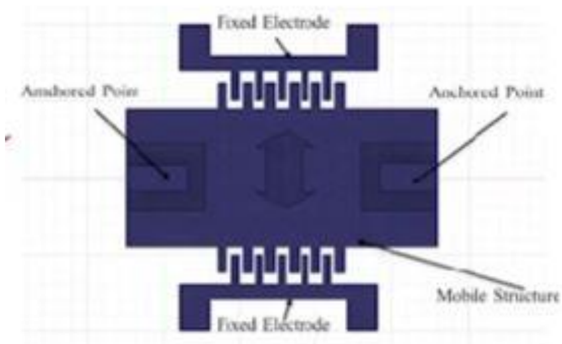
In the last lecture, we discussed the different configurations of gyroscope accelerometers, their advantages, applications, and overall characteristics, including the optical-based gyroscopes. They are kind of less mechanically based gyroscopes, which can be efficiently used in the case of micro-robotic-related applications. We also discussed the mechanical switches and their different configurations. As an extension of the mechanical switches, we will now discuss the MEMS-based switches. MEMS-based switches are microscopic devices that combine electrical and mechanical components. However, the fabrication of these MEMS-based switches is a challenging task.

Now the fabrication techniques are advanced enough so that we can fabricate customized MEMS-based switches. We can develop customized MEMS-based switches based on the requirements. The key features of the MEMS-based switches are, firstly, that they have a miniaturized size, basically in microns to a few millimeters. They have low mass and high responsiveness, as well as a capability for seamless integration with electronic circuits.

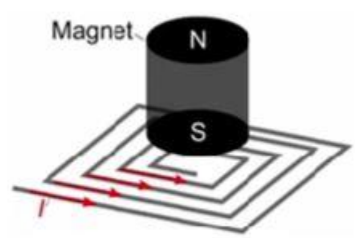
The different types of MEMS-based switches include capacitive and ohmic MEMS switches. They find applications in RF circuits, telecommunications, and signal routing. Now we will discuss the different configurations of the MEMS switches. So the first switch that is widely used is the electrostatic switch. Earlier, we discussed considerably about the comb drive actuators which work on the principle of electrostatic switches.

In the comb drive actuators, the major components include a fixed electrode and an anchored point. The figure shows the anchored point and the fixed electrode. The movement and the restriction can be affected using this assembly. Now the restriction of the displacement can also be through electrostatic charge, i.e., if we need to restrict the X plane, Y plane, or Z plane, we can appropriately create a resistance with electrostatic charge and limit the overall actuation. For example, if I want to move at an increment of around 0.25 micrometers, then it is possible with the electrostatic structure. Let us consider that there are two comb drive structures and the movement between them is nearly 0.5 micrometers.

Electrostatic switch



We need to initiate a step size of 0.25 micrometers, so by controlling the electrostatic charge between these two plates, we can have control over the step size displacement. There are different configurations that exist which provide the rotation of the actuator. As shown in the figure, the two electrodes are kept in different planes, and a twisting moment can be given to one of the electrodes, resulting in a micron-level rotation. The restriction in this micron rotation can be controlled using the electrostatic component. Now let us talk about the electromagnetic switches. An example is shown in the figure. Suppose there are two magnets facing each other with their north poles. When two magnets are facing each other with the same polarity, they experience a repulsive force. The control of this repulsive force can be taken care of with reference to the field as well as the gap between these two magnets.



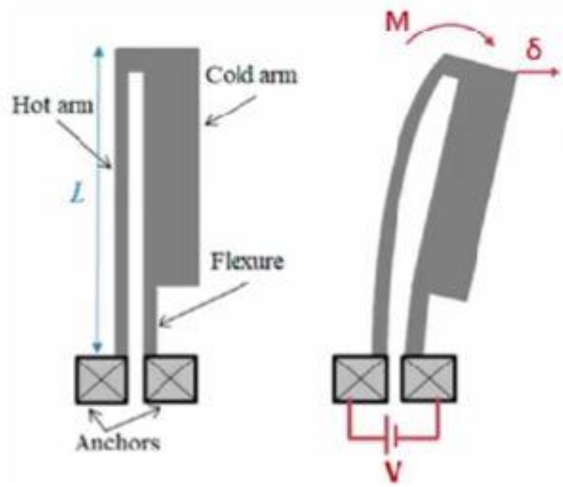
Electromagnetic switch

Similarly, let us consider an electromagnet where the top portion has the North Pole. In order to have a step displacement, we can reverse the polarity. So, whenever attraction is required, a polarity is created such that the electric field has a South Pole in it, and then the magnet is attracted, and immediately as it reaches a particular position, we can switch the polarity such that a North Pole will be generated, which hinders the motion so that we can create a step displacement. The interesting part of this is that if we generate a stick-slip kind of actuator, its position can be controlled by electromagnetic coils that can be embedded, or the electromagnetic sensors that can be embedded, which will be helpful to restrict the movement of the system. Now let us discuss the electrothermal switches.

The main principle behind the electrothermal switches is that, suppose we have an object, and if we supply an electrical bias to the metallic object, there will be a kind of change in the displacement; i.e., when you try to supply an electrical bias to a metal, this metal will try to expand, and this thermal expansion of the material will create motion. The figure shows one configuration of the electrothermal switch; in this particular configuration, there are two anchors. A flexure member is connected to a cold arm and a hot arm, as shown in the figure.

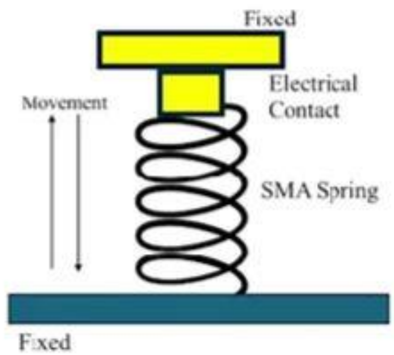
Electrothermal switch

Through the anchors, we supply electrical biasing to the switch so that the hot arm expands



due to thermal expansion; therefore, there will be a deflection from the hot arm. In this particular case, the material will expand based on the thermal expansion coefficient property of the material. Now, one option is to give a pulsed biasing to the element, which provides control over the overall step size of these arm structures. This is one way. Another way involves the concept of a unimorph and a bimorph.That is, we have two materials in combination. One material is supplied to a bias. However, the other material acts as an elastic medium. So, when we supply an electrical bias to this structure, there will be a kind of expansion in this structure. The expansion of this structure can be restricted with the help of the elastic element, and thus, expansion can be controlled.

Similar switching can be seen in the case of shape memory alloy biomorph, where initially, SMA will be in a coiled state. When we supply an electrical bias to it, SMA gets actuated, and then there will be a forward stroke, and upon switching off the power, the return stroke happens. The forward stroke will have a higher displacement, and the control of the reverse stroke is maintained because of the elastic medium, which participates along with the shape memory material in the bimorph structure. So as far as the electrothermal switches are concerned, there are three main types of switches. One is a kind of hot and cold arm-based electrothermal switch, the second is a chevron-based system, and then there is a bimorph-based configuration used for switches.



Shape memory alloy-based switch

There are wide varieties of applications of using these bimorph configurations. The electrothermal switch exhibits a larger displacement force at a low voltage ranging from 0.5 to 5 volts; thus, the configuration can be easily controlled. We already have good exposure in fabricating these kinds of structures using the bottom-up approach. In the case of the bottom-up approach, we can print the structures based on requirements.

In fact, it might either be a mask-based or a maskless base. We appropriately select the material where improved tunability is achieved by giving a different geometric configuration to the system. Now, let us discuss a shape memory alloy. In a shape memory alloy, we have already seen that it is switching between an austenite and a martensite phase. Let us consider a rod. This rod is initially in the form of a martensitic phase at room temperature. Now, when we deform it, it becomes detwinned martensite. When I try to supply heat to it, it changes phase to an austenite phase and then it returns to the martensite phase upon cooling. The deformation or actuation behavior is appropriately taken care of by the phase transformation. Both these systems come under the category of the thermal domain.

In this thermal domain, the movement restriction or the movement of actuation can be applied by giving a temperature gradient to the system. By applying a temperature gradient appropriately, there will be deflection. These materials return to the predetermined shape when heated. For example, if we consider a shape memory switch, in fact, this is a kind of direction flow control wall. The shape memory alloy switches are integrated into the walls of this DCV. So under the initial condition, the flow is restricted. If we need to change the flow, we supply an electrical bias to this system; this spring will actuate appropriately for movement. The movement of the block in the figure will be helpful for us to have flow control. These are some kinds of specialized switches. Conventionally, we can use a simple shape memory alloy spring.

So, using a simple shape memory alloy spring, we can apply a bias to it, and we can have control over the overall movement of the block. These were some of the basic configurations that are available. There are other wide varieties of configurations that are being deployed based on the customized requirements, applications, and different domains. Now, let us see some of the key performance parameters for these microswitches, especially the MEMS-based microswitches. So in that aspect, the first important parameter is the switching time.

So as far as this switching time is concerned, like in all four cases, a transition between different states exists. The speed of the transition between the states plays a vital role. For example, in the case of an electrostatic switch, when there is a change in the charges or a shifting of the charges, there is going to be a change in the orientation of the magnetic field. In the case of electrothermal switches as well, the entire process depends on the thermal conductivity and the specific thermal expansion coefficient of the material. So, based on the thermal expansion coefficient, the overall response of the switches depends.

Then, with reference to shape memory alloy switches, their switching occurs between the austenite and martensite phase transformations. So, this switching between austenite and the martensite transformation requires some time for relaxation or for reaching its particular state. Based on the speed of the transformation between the states, the applications are decided. In fact, when we consider the concept of bimorph as well, these elastic members will take some time for retraction, which determines the transition between the states. Now, let us talk about the ranges of the switching time.

The range of switching time actuates plays a vital role. It ranges from a microsecond to a millisecond, basically when we use such kinds of systems for micro-robotics-related applications. The third important point is with reference to application suitability in the case of a high-speed system. When there is a requirement for kilohertz frequency, the usage of such a thermal system will not be possible because it has limitations with reference to response time. However, in the case of electrostatic switches, it is possible.

Even piezoelectric-based switches can also be deployed to attain such frequencies. Next is with reference to the transmission performance. There are two sets of transmission that come into the picture. One is a signal; another is a load. Considering the load on a micron-level scale, such kinds of loads are highly negligible.

Considering the transmission performance, the insertion loss basically causes the signal power loss in the on state and is considered to be one of the major parameters for restricting our movement. Second is with reference to return loss, which is a reflected power due to the impedance mismatch; that is, we are supplying an input, and we get a reduced output from it. In certain cases, because of the deviation in the impedance, there are some kinds of mismatches that occur. The third important characteristic is isolation. Isolation is the ability to prevent signal coupling between the ports.

Next, when we have the contact resistance, the resistance at contact points affects the efficiency of the particular system and is one of the major concerns of micro devices that are used in micro robotic systems or similar systems. Establishing a contact is a challenging task; that is the reason we have been emphasizing contactless charging or a kind of self-powered system, as it has its own advantages with reference to the reduction in size and improvement in the efficiency of the system. Second, with reference to the figure of merit, R on and C off, and third, lower values of contact resistance indicate better performance. Now considering the reliability of the systems of these devices. Consider a switch that is integrated with the bimorph-like structure and is limited to a particular portion.This switch gets activated back and forth and it is restricted at this particular position which will be helpful for us for position limiting. One of the important parameters is frequency. So, we can increase the frequency or decrease the frequency within a particular limit. Now, the system is expected to have a complete reliable or a complete repeatability process throughout. So, this is judged on the basis of life cycle performance, which includes switching and de-switching.

Therefore, this needs to be continuously monitored throughout, and this should remain constant. However, in certain cases, there are additional components aggregated into it. That is what we had discussed regarding the residual stress that is being generated. We had also discussed the hysteresis that occurs in the case of a piezoelectric structure. So there is a need for hysteresis compensation in such components.

The next important parameter that affects reliability is the material fabrication and the operational conditions. The third important aspect is with reference to dielectric charging and the aging effect. Dielectric charging and discharging, along with the aging effect, slowly affect the reliability characteristics of the system, which may decrease. For example, let us consider a shape memory alloy cantilever which is used for switching behavior between point A and point B. Consider point A at the down position and point B at the up position of the cantilever. By applying an actuation to it, it reaches point A, and by applying an actuation to it, it reaches point B. Now, the overall life cycle behavior is down position A and top position B in an alternating manner, as shown in the figure. Now consider the fundamental mechanism of motion. We are applying a thermal cycle to it through an electrical charging system, i.e., via Joule heating. We apply electrical biasing by giving a kind of step input or sweep input to it, so that this actuation is taken care of. With heat transfer involved in the process, the material will try to attract the kind of oxide from its surroundings. The more these oxides start entering the lattice of the material, the more this lattice will restrict the overall deflection of the cantilever. So, in due course of time, this lattice will start absorbing this oxide, which will result in defragmentation, and finally, it will result in the failure of the system.

So, this is one example of an aging effect. This also talks about the operational condition of the material. That is, if you want to have a higher reliability, one of the major factors that impact the overall fatigue behavior is the oxide formation. Now, when we try to conduct this entire process in a packaged condition where the overall oxygen depletion is restricted, we can achieve an improvement in the life cycle behavior. Now considering different applications of these microswitches, which include the keypad, button, touch interface, and appliance control and safety mechanisms, as well as gaming controllers and input devices primarily for consumer electronics. It also has potential applications in safety systems like airbags and braking.

It also has a good number of potential applications in comfort controls, including the windows, seats, lighting, engine management, and sensor systems. The door and compartment systems, especially today, have a significant impact on the e-vehicle. Next is with reference to the telecommunication perspective point of view. So, we have the signal routing and the antenna switching system. The network infrastructure, equipment system and the mobile device components play a vital role in the telecommunication system. From an automation perspective, it is used in control systems and safety interlocks. It is also used in production line monitoring and is effectively used in robotic systems and equipment interfaces. In medical devices, it is used in patient monitoring equipment, surgical tools and precision instruments, diagnostic devices, and laboratory equipment. In robotic and micro-manipulation applications, it is used for precision positioning, micro grippers and actuators, surgical robots, and as a minimally invasive tool, like the magnetic micro robots we have been discussing in relation to the surgical tool. For those conditions, we apply the electromagnetic field to restrict movement.

Next is with reference to aerospace-related applications. So, it is applicable in control systems, navigation equipment, and mission-critical safety mechanisms. So, these are the applications in the industry. Now some of the major advantages of this system are that it has physical feedback during operation. It has simple and reliable operating principles.

It has direct visual confirmation of the slide. It has the ability to handle high currents. It has minimal signal interference. It is highly used for precise operation in harsh environments. With reference to challenges from a perspective point of view, we have mechanical wear and fatigue over time, contact degradation, and resistance changes. There are size limitations in the case of miniaturized applications and slower switching speeds compared to solid-state systems.

It is highly environmentally sensitive, especially with reference to the dust and the moisture. The striction issue in microscale devices is one of the key issues that has to be addressed. Recently, there are a wide variety of switches being effectively used in micro-robotics applications. One of the switches is a type of hall effect switch that is a type of micro power hall effect switch, which uses both magnetic and electric fields and tries to enhance the charge.

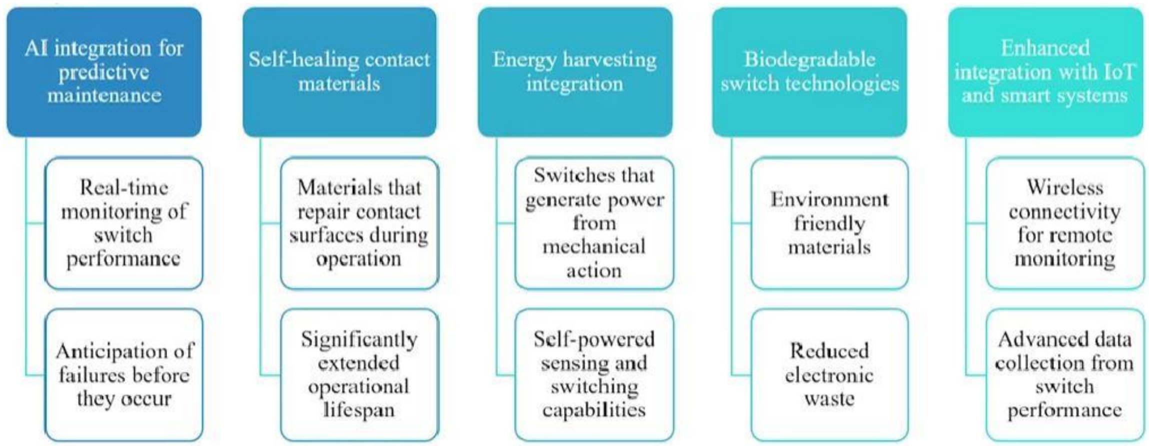
It's a type of ultra low energy switch. It has ultra low energy consumption and extended battery life for portable applications. With reference to sensing, a piezoelectric actuator and triboelectric materials were discussed. This has an advantage of self-sensing related application. That is, when we apply a load, so there is a potential difference created across the material. Owing to its potential difference, the signal can be fed back for appropriate self-sensing related applications.

Thus, combined sensing and actuation capabilities are possible. It eliminates the need for a separate sensor component. With reference to polymer-based electromagnetic actuators, they have enhanced flexibility and adaptability, which is considered to be the major advantage; most importantly, programming them is quite easy. Most of these polymer-based electromagnetic actuators are biocompatible for medical-related applications. With reference to multi-material MEMS with enhanced reliability, these advanced materials reduce friction and wear.

They have improved performance in harsh environments. One of the important aspects is that soft electromagnetic actuators utilize these liquid metal channels in elastomeric shells, which can be applied in soft robotics and flexible devices. So, these are some of the recent advances in microswitches. The future perspective is more focused on AI integration for predictive maintenance. The real-time monitoring of switch performance and anticipation of failures before they occur is one of the key points and key challenges that have been addressed in recent years. This holds good not only for micro switches; it also holds good for the entire micro robotic-related systems.

Then we have a self-healing contact material that repairs the contact surface during operations, and it significantly extends the operational lifespan. For energy harvesting integration applications, the switches that generate power from a mechanical action might be either piezoelectric or triboelectric. Self-powered sensing and switching capabilities can be employed. Next, with respect to biodegradable switch technologies from a perspective point of view, it is an environmentally friendly material and it has reduced electronic waste.

It has enhanced integration with IoT systems and smart systems. The wireless connectivity for remote monitoring and advanced data collection from switch performance is considered to be one of the key parameters for enhanced integration with IoT and smart systems.



Future Trends