Microrobotics

Prof. Palani Iyamperumal Anand

Department of Mechanical Engineering

Indian Institute of Technology, Indore

Week- 05

Lecture No- 24

Microactuation and Micromanipulation - Module 09

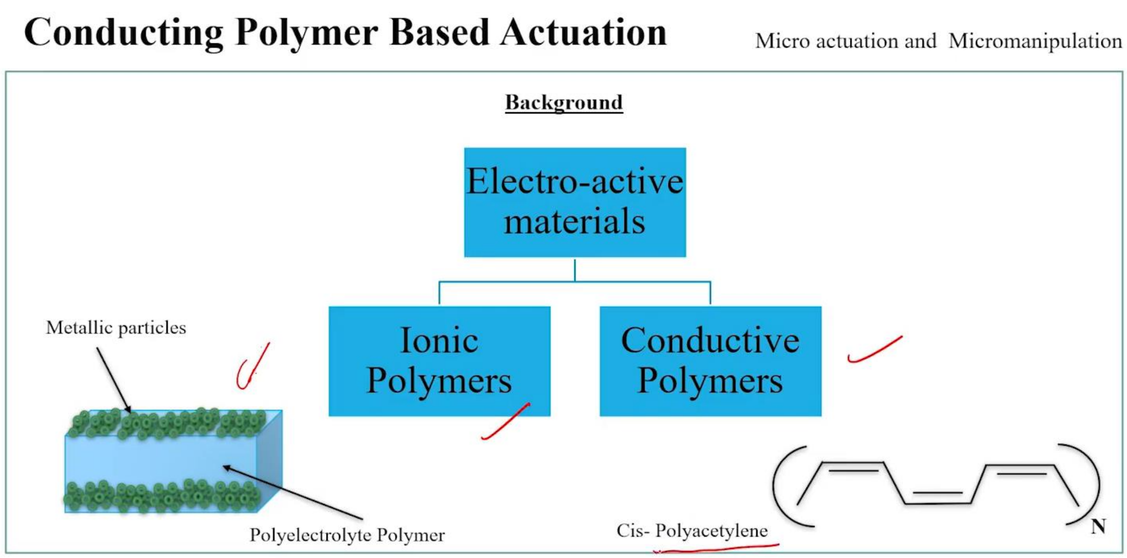
In the next module, we will discuss this conducting polymer-based actuation and a stick-slip-based system. So as far as this conducting polymer-based actuation is concerned, there are a wide variety of polymers that have been demonstrating this actuation mechanism. One of the polymers that is efficiently used is called an electro-active polymer. These electro-active polymers are inert materials that can deform up to 300% of their initial shape, and they have the capability of generating a large force compared to the strength of human muscles. Since it's a polymer, it almost has a capability similar to that of human muscles, so these kinds of conductive polymers are efficiently used for such applications. Now, when we try to classify this electro-active polymer, these electro-active polymers are classified into two categories: one is called an ionic polymer and the other is called a conductive polymer.

These ionic polymers are concerned, so they are a type of polyelectrolyte polymer that is integrated with metallic particles. These metallic particles, when integrated with polyelectrolyte-based polymer, have potential applications in actuation. However, with reference to this particular conductive polymer, we have polyacetylene, which is being captured or used for different applications. Now let me just introduce you to this conducting polymer-based actuation.

This conducting polymer-based actuation is concerned; this is an exciting field where a special material can change shape when electricity is applied. It almost works like a muscle. However, in the case of conducting polymers, they exhibit electronic conductivity, making them unusual among organic materials. These are a wide variety of chemical structures of some conducting polymers, such as polyaniline and trans-polyacetylene. This cis-polyacetylene and polypyrrole are some of the different conducting polymers that are being efficiently used for a type of micro robotic applications.

Now, when we try to look into the basic principle of actuation, these conducting polymers can easily lose and gain electrons when voltage is applied. So, when it is immersed in a medium containing ions, they will attract or repel certain ions. This will expand our contract after this exchange. This property can be exploited, and it can be used as a type of actuator, essentially for micro-actuations. Now, some of the unique properties of these conducting polymers are that a defining structure of a conducting polymer is its conjugated backbone, which enables it to have some degree of electron delocalization, and hence it is suitable for electronic conduction.

Now there is a process of doping that involves the addition or removal of charges from the polymer chain, resulting in structural changes and the creation of states in a band gap. Thus, the doping process also produces a volume chain. These dimensional changes are used to perform mechanical work. Thus, actuation in conducting polymers is derived from a dimensional change associated with the change in the polymer oxidation state. Now, when we try to look into the overall mechanism of these actuations, the way these actuators work is mainly through a process called ion doping and de-doping.



That is, when you apply a voltage, the polymer either gains or loses an electron, as discussed before, to balance this. These ions, these tiny charged particles, move in and out; this can make the polymer expand or contract. So there are two main types of configuration or mechanisms that persist with reference to actuation. One is called an anion-driven process, in which a small ion enters or leaves, causing the polymer to grow or shrink. The second one is called a cation driven; it's a large ion that stays put while other ions move in, leading to an expansion or contraction.

Now, when we try to see the history behind the operation of this actuator, So, this conducting polymer was first discovered by a person named Shirakawa, Alan, and Alan Heeger. They were awarded the Nobel Prize in Chemistry for this discovery and the development of conducting polymers. This invention happened accidentally when a polymer was placed near a kind of furnace; because of the heating, it could activate the electrical behavior of this polymer, which later resulted in a type of conducting polymer for the system. So, if you closely observe these conducting polymers, they have the capability to actuate; they can hold the system and relieve the system. So, when an electrical contact is applied to it by actuating it, it can actuate at different dimensions.

So, appropriately similar to shape memory alloy, a kind of shape setting needs to be incorporated here as well. So this shape setting has the capability to generate a kind of shape. So the interesting part of this conducting polymer is that these conducting polymers can be actuated in any kind of medium. In fact, that's how this has opened up a new domain in such a way that it is similar to the case of underwater manipulation or underwater explorations. Such kinds of conducting polymers can be efficiently used for handling some organisms or some materials in underwater conditions.

Now, when we try to look into the fundamental principle of actuation in the case of a conducting polymer, the electrochemical doping and the electrochemical de-doping processes exhibit. So the actuation mechanism in conducting polymers is primarily based on the electrochemical doping and de-doping process. So when an electrical potential is applied, the polymer undergoes oxidation or reduction, leading to changes in its electronic structure. Now, there are two different configurations that exist: one is called the volume change and the other is called the conformational shift. As the polymer oxidizes or reduces, it experiences a volume change due to the insertion or expulsion of ions and solvent molecules.

These volume changes are accompanied by a conformational shift in the polymer backbone. When we try to talk about ion migration and solvent interaction, the doping process involves the migration of ions between the polymers and the surrounding electrode. This ion movement, along with the associated solvent interactions, plays a crucial role in the actuation mechanism. In fact, you might have heard a lot about this osmotic effect. This osmotic effect causes a solvent molecule to move into the polymer in a number far exceeding those bound in the solvation cell of the mobile ion, resulting in a significant volume, thus leading to a kind of structure.

Conducting Polymer Based Actuation

Micro actuation and Micromanipulation

Introduction

- Conducting polymer-based actuation is an exciting field where special materials can change shape when electricity is applied, much like how muscles work.
- Conducting polymers exhibit electronic conductivity, making them unusual amongst organic materials.

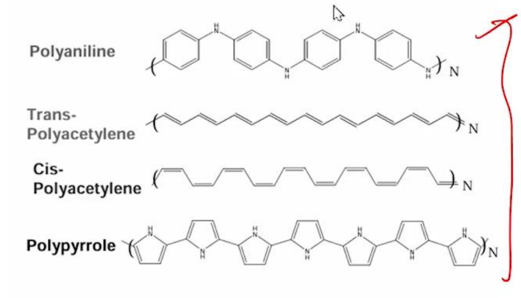


Fig. Chemical structures of some conducting polymers

So when we try to observe the different types of conducting polymers, there are commonly two types of conducting polymers that exist. One is called polyaniline, which we refer to as PANI, and the other is called polypyrol. This polyaniline and polypyrrole are some of the key conducting polymers that are used in micro robotic systems. So polyaniline is one of the most studied conducting polymers due to its environmental stability and simple synthesis process. It exhibits good electrical conductivity, and the electromechanical process makes it suitable for actuation applications.

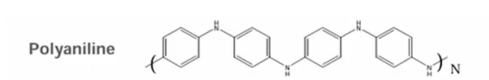
Conducting Polymer Based Actuation

Micro actuation and Micromanipulation

Common types of conducting polymers used in actuation

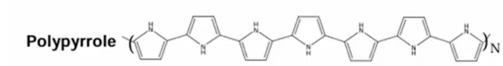
- **Polyaniline (PANI)**

  Polyaniline is one of the most studied conducting polymers due to its environmental stability and simple synthesis process. It exhibits good electrical conductivity and electrochemical properties, making it suitable for actuation applications.



- **Polypyrrole (PPy)**

  Polypyrrole is widely used in actuator research due to its high conductivity, good environmental stability, and large actuation strain. It can be easily synthesized through chemical or electrochemical methods.



With reference to the polypyrrole perspective point of view, polypyrrole is widely used in actuator research due to its high conductivity, good environmental stability, larger actuation strain, and its ease of synthesis through a chemical or electrochemical method.

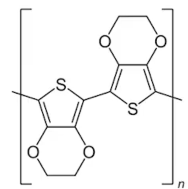
Similarly, there is a kind of conducting polymer called PEDOT, which is poly(3, 4-ethylenedioxythiophene). This PEDOT, especially when it is combined with poly(styrenesulfonate) (PSS), to form a PEDOT:PSS. This PEDOT:PSS has gained attention in recent years. It offers excellent conductivity, transparency, and processability, making it suitable for various actuation applications.

Conducting Polymer Based Actuation

Micro actuation and Micromanipulation

- **Poly(3,4-ethylenedioxythiophene) (PEDOT)**

  PEDOT, especially when combined with poly(styrenesulfonate) (PSS) to form PEDOT:PSS, has gained significant attention in recent years. It offers excellent conductivity, transparency, and processability, making it suitable for various actuation applications.



So these are some of the advantages of using this PEDOT:PSS and utilization of these PEDOT:PSS for different applications. Now let us discuss the various actuation mechanisms that exhibit for actuating these conducting polymers. One is called an electrochemical actuation. So, electrochemical actuation is the most common mechanism in conducting polymer actuators. It involves the application of an electrical potential to induce a redox reaction, leading to ion movement and volume change.

The next one is called an electrothermal actuation. As far as this electrothermal actuation is concerned, some conducting polymer actuators can be activated by joule heating. That is, when an electric current passes through the polymer, it generates heat, causing thermal expansion and contraction. By supplying heat to it, appropriate thermal expansion and contraction occur. Then the other process is called photo-induced actuation.

So, photo-induced actuation, as the name suggests, is what we can do using a light. So, the light can be efficiently used, or it can be absorbed by these conducting polymers, and appropriately there is a kind of actuation that persists. So, certain conducting polymers can exhibit an actuation response to light stimuli, and this mechanism is less common but offers potential for remote actuation in specific locations. In fact, a similar case study we had seen in the earlier case also involved a laser being used to actuate the shape memory alloy for appropriate motion or propulsion. Now, some of the key properties and characteristics of these conducting polymers are of concern.

These conducting polymers are a kind of strain and stress generation. That is, conducting polymers can generate strains typically in the range of 1 to 2 percent; some advanced systems have achieved higher values. As far as response time and frequency are concerned, the response time of the conducting polymer actuator is generally in the order of seconds to minutes. Depending on the size and configuration of the actuator, the actuator speed is often limited by the rate of ion diffusion. Now, when we try to talk about the efficiency and energy density of these conducting polymers, the energy density of the conducting polymer actuator is compared to that of a mammalian skeletal muscle.

However, their efficiency is typically low, often less than 1%. Which means that it has a higher energy density and has potential applications in biomimicking-related areas as well as biomimicking-related domains. However, from an efficacy perspective, it is very low. The next important aspect with reference to the usage of conducting polymers for micro robotic applications is the cycle life and stability. So, improving the cycle life and long-term stability of a conducting polymer actuator remains a significant challenge.

The current system can achieve close to thousands of cycles, but degradation over time is still a concern. Now, let us see some of the different device architectures of this conducting-based polymer. One device architecture is called a bilayer actuator. The bilayer actuator consists of a conducting polymer layer bonded to a passive layer. When the polymer layer expands and contracts, it causes the entire structure to bend.

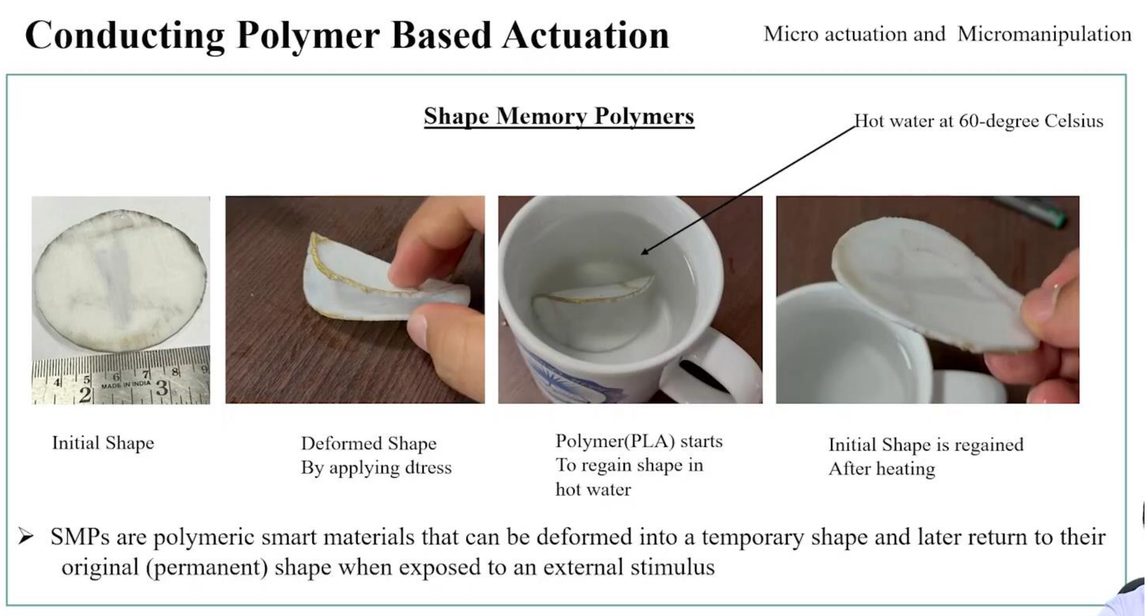
So, there is a kind of conducting polymer and a host matrix that is available. So, it is connected to the anode and the cathode. So what happens is that when we try to apply a bias to it, there is a bending in the system, and when we try to actuate it, it returns to its shape. Similarly, it is almost equivalent to a kind of biomorph system that we discussed earlier for shape memory alloy. The actuation of the conducting pole of the system is taken care of by the conducting polymer for bending.

However, the host matrix acts as a kind of support structure so that it participates in the actuation; when the return stroke is happening, this host matrix will participate, and it will ensure the return stroke next. We have a kind of trilayer actuator. The trilayer actuator typically comprises two conducting polymer layers separated by an electrolyte-containing layer. This configuration allows for bidirectional actuation. In this bidirectional actuation, if you see the overall configuration, there are two conducting polymer layers available, and in between, we have a kind of host matrix.

When we try to actuate this host matrix, one is being trained to actuate in one direction and the other one is trained in the opposite direction. However, the host matrix acts as a buffer layer in such a way that it will try to compensate for both the actuation in the positive as well as in the negative direction, or I can say it can support the actuation in both directions. So that's how it can work. Now, when we try to talk about the application of these conducting polymer-based systems, these conducting polymer-based systems are efficiently used for biomedical applications, especially in conducting polymer actuators that are being explored for use in minimally invasive surgical tools, drug delivery, and artificial muscles for prosthetics. As far as soft robotics is concerned, it has potential applications.

It has high flexibility and biocompatibility as a conducting polymer actuator, which makes it attractive for soft robotic applications, including grippers and locomotion systems. From a microfluidic perspective, conducting polymer actuators can be used as walls and pumps in microfluidic devices, which offer precise control, as in the case of a microfluidic chip. Therefore, we can have control over actuation. Now, with reference to future direction and perspective, it has an improved actuation performance; there is various ongoing research focused on enhancing the strain, stress, and response time through material optimization and novel device architecture, either by working on the chemical bonding or the behavior of conducting polymers. There is some research that focuses on the training of these conducting polymers for different applications.

So there are some explorations where the conducting polymers are actuated through different domains including magnetic, electric, light, heat, and moisture. Enhancing the long-term stability by improving the cycle life and environmental stability of conducting polymer actuators remains a key area of research. As well as from a novel fabrication technique perspective, these advanced manufacturing methods, such as 3D printing of conducting polymers, are being explored to create complex structures. Let us see some of the conducting polymer-based actuations. In fact, this is one shape memory alloy-based polymer that is being created.



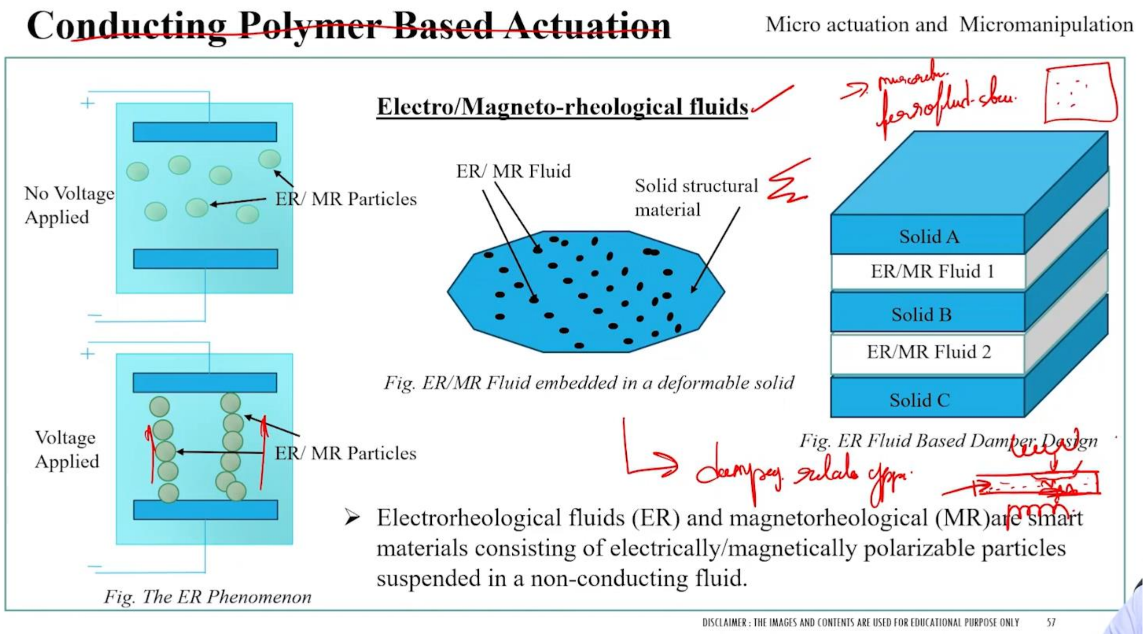
So initially, this is a kind of initial shape. It is being deformed by an applied stress and then the PLA starts. So here, the PLA is integrated into it. Then it regains the shape. So this is almost like a PLA coupled with shape memory or polymer.

So what it tries to do is deform it, and through hot water actuation, we can regain its original shape. The hot water is at a temperature of around 60 degrees, which is quite sufficient. In fact, from a micro actuation perspective, small micro cantilevers can be fabricated using this particular technology. And this particular technology can be embedded appropriately in such a way that, by using hot water spraying, we can go for selective actuation. For example, if this kind of structure is present, by spraying and using hot water actuation, we can appropriately displace it to obtain the structure.

These shape memory alloy polymers are polymeric smart materials that can be deformed later, and they can be actuated through an external stimulus. This is an interesting conducting polymer that is called an electromagnetic rheological-based fluid conducting system. So, in this electromagnetic context, what we are trying to do is like the electromagnetic rheological fluids and matter that are smart, consisting of electrically and magnetically polarized particles which are suspended in a non-conducting fluid. So ideally, these are called electromagnetorheological systems. So, what happens is that in this fluid, the particles are dispersed as shown over here.

When a voltage is applied appropriately, it tries to take shape. So, when it tries to take shape, it aligns in a particular domain so that this alignment will be capable enough for it to move in a particular direction, and this can be used for different applications. In fact, there are ferrofluidic structures that are like micro robotic ferrofluidic structures. So, this structure is something like a complete nanoparticle that will be dispersed in the liquid medium, and then a kind of fluctuating magnetic field will be applied. These fluctuating magnetic fields are capable of energizing and aligning these ferrofluidic structures, and finally, they form a kind of sculptural arrangement.

As far as these ferrofluidic structures are concerned, they are efficiently used for microrobotics applications; especially by giving an external actuation, you can align the nodes, and appropriately, you can use it for the kind of actuation behavior. In other words, it is also used for damping-related applications. For instance, this is a kind of biological wall; inside this wall, the liquid is made to pass through it. This liquid contains a certain amount of these solid structural materials, which are called electro- or magnetorheological particles. These electro- or magnetorheological particles are made to flow through this particular tube, and now, when they are made to pass through this tube, let us consider that there is some kind of obstruction here that needs to be removed.



The mechanism can be deployed in such a way that an actuation field can be applied. This actuation field will induce a certain amount of structure, something like this. These structures can be actuated so they act as a kind of drilling unit or as a kind of grinding wheel that grinds the fatigue content or a kind of solid content that is available. Then it can be completely eroded and flushed away along with the system. Such kinds of biologically related applications can be deployed using this magnetorheological.

In biomimicking, as well as in the micromanipulation related to biomimicking, we will be discussing a lot about this with different case studies. Overall, we had discussed the conducting polymer, the different types of conducting polymers, the capabilities of these conducting polymers, the classification of these conducting polymers, the overall basic principle and actuation involved with these conducting polymers, the unique properties of these conducting polymers, and the mechanism of actuation. So, we have also discussed the characteristics of these conducting polymers, the fundamental principle of actuation in relation to conducting polymers, and the common types of conducting polymers used in actuation, such as polyaniline, polypropylene, and PEDOT:PSS, which are available. Different actuation mechanisms are deployed, which include electrochemical reactions, electrothermal reactions, and photo-induced reactions. There are different key characteristics that pass, which include stress generation response efficiency and energy density, etc.

There are different device architectures being established using this conducting polymer, such as unimorph-based and bimorph-based systems, which are well established using this conducting polymer technology. The conducting polymer has a wide range of applications, which include biomedical devices, soft robotics, microfluidics, etc. It has quite a good amount of future directions regarding actuation, longer-term stability, and novel fabrication techniques. And then this is an example of how conducting polymer-based actuations are being done. In fact, here a PLA is taken and appropriately it is being taken up.

Other sets of such smart actuators include a magnetorheological-based system. So these magnetorheological-based systems are kind of fluid or gel-based systems that are integrated into the environment or domain, and appropriate actuations are deployed to achieve different characteristic behaviors. So now we will discuss, so let us go to the next part, which is stick slip, and we will be discussing it in the upcoming classes. We have discussed a lot about these shape memory alloys. In fact, we have discussed how the different locomotion of this shape memory alloy exists and what the different configurations of shape memory alloys are, etc.

Now, as far as these are concerned, whenever we are trying to construct these shape memory alloy micro actuators, there are certain design principles that are present. So if we try to correlate the design principles, it will be efficient enough for us to use it for different applications, including locomotion related to pick-and-place arrangements or feeders, etc. So, let us discuss some of the configurations related to these SMA design principles. One of the important configurations is called a bias spring-based configuration. In this bias spring configuration, it is the first time an intuitive approach is used to employ a mechanical element that constantly supplies force on the material.

So this mechanical element can be either a kind of bias spring, a kind of antagonistic design, or a dead weight. So let us see how the configuration looks. In this configuration, let us consider this as a biased spring, and this is a kind of shape memory alloy that exists. Now, in this particular configuration, this is called a bias spring. Let me just represent it as BS; BS is nothing but the bias spring, and this is the shape memory alloy.

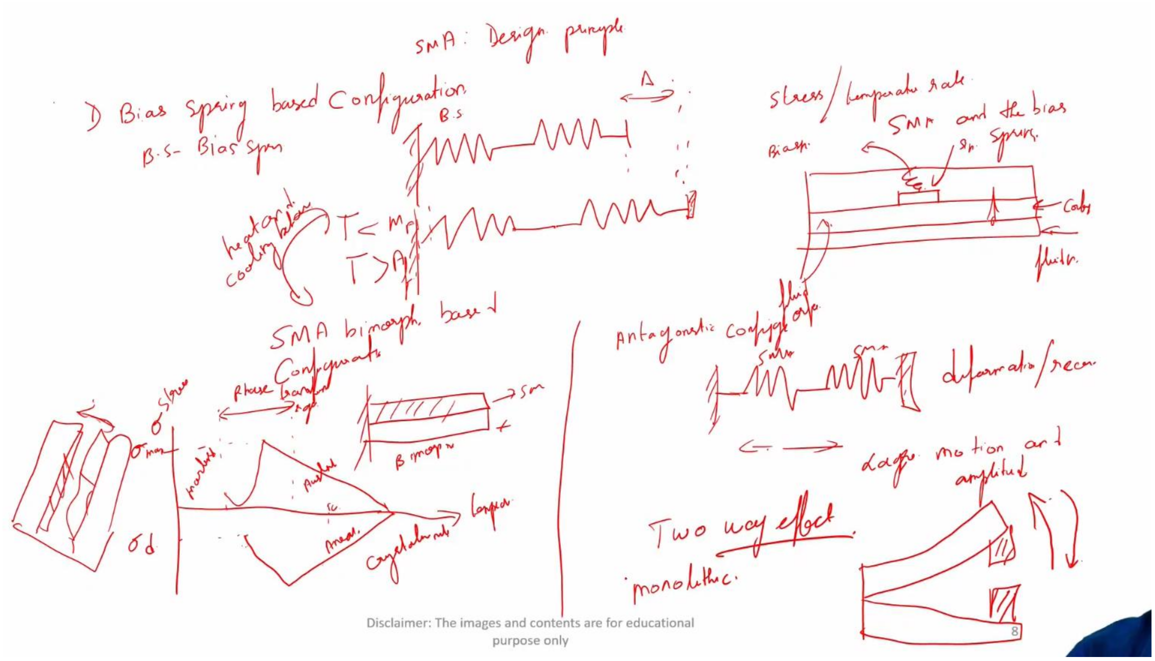
This is a kind of fixed structure, and del is a kind of deformation behavior that moves. So in this particular case, we can have two different conditions: one is when T is less than the martensite finish, then we can have the expansion. With reference to bias and SMA so that it reaches this particular point. Now, in addition to this, this condition can be applied in both cases: one is when T is less than the martensite finish, and the other is when T is greater than the austenite finish. So in both these conditions, we can exhibit this structure; the only thing is there will be a kind of cycle between heating and cooling behavior.

Now, as far as this particular case is concerned, the system consists of a bias spring, and the SMA is pre-strained by a deformation delta attached at both ends, so that the system remains in a deformed state after mounting, and this deformation induces a reorientation of the martensite variant. The equilibrium point in this case is found to be looking for an equilibrium between the force applied by the SMA and the force resulting from the bias spring action. Upon heating, the material tries to regain its original shape; martensite turns into austenite, resulting from an increasing force towards the SMA spring, which we call state 2. On cooling, the martensite variants nucleate, but instead of being homogeneously distributed as would happen in the case of stress-free cooling, the variants orient themselves so that the stress resulting from the pulling force applied by the spring on the SMA is minimized. As a consequence, the equilibrium shifts towards the bias spring at this time.

In order to find this, there are different methods that are available. So one method, in fact, we had also demonstrated was a kind of Michelson's interferometer. Using a Michelson interferometer, we can calibrate the spring. So we can study the overall fatigue life behavior of the springs. Some of the key aspects when we try to observe using this configuration are that the maximum stress the system will experience upon shape recovery depends on the amount of preloading and the stiffness of the bias spring and the SMA used.

Similarly, one more aspect is that the stress versus temperature rate will depend upon the stiffness ratio between the SMA and the bias spring. In fact, these kinds of bias springs are effectively used in a certain amount of walls, etc. So, in fact, I can just show you one simple configuration. Let us consider this as a kind of poppet wall.

So, in this poppet wall, there are two configurations. So in this configuration, we have an arrangement where a spring is available. This is a kind of bias spring, and then we have an SI pop-up in place. So we have a control pressure and fluid that is being integrated over here, and then there is a kind of fluid orifice arrangement. This fluid orifice will take care of the overall modulation between the structure. This is one configuration which is called a bias spring-based configuration, and the other configuration we also call an antagonistic configuration.



So in the case of an antagonistic configuration, we will have two shape memory alloys: shape memory alloy 1 and shape memory alloy 2. There will be a set of configurations in such a way that whenever we need to have an expansion in this direction, the variant will be a kind of simple bias spring actuator principle where it uses two shape memory alloy elements. It consists of mounting two SMA actuators opposite each other. As for the bias spring, the system consists of two coupled actuators that provide the first pre-stress, so both actuators are deformed. So these are SMAs from their parent phase shape during this step when an actuator transforms and deforms its counterpart.

By alternatively heating the two actuators, a sequence of deformation and recovery is introduced, leading to a kind of reversible motion. Although the working principle is relatively simple, such linear actuators have highly nonlinear characteristics. So the behavior can be seen from the phenomenon of the neomological point by examining the characteristics. So basically, wherever we require a large motion and amplitude, such kinds of antagonistic configurations are introduced.

Next, we have a kind of SMA bimorph-based configuration. As far as this SMA bimorph-based configuration is concerned, we have a kind of SMA bimorph configuration. We have two SMA structures; one is a kind of smart material, and the other one will cater to the overall deformation that exhibits in this particular structure. So, like we have seen these combinations where it is in such a way that when we try to actuate the shape memory alloy, the shape memory alloy gets actuated and then there is going to be a polymer structure. This polymer structure will also be actuated along with the shape memory alloy.

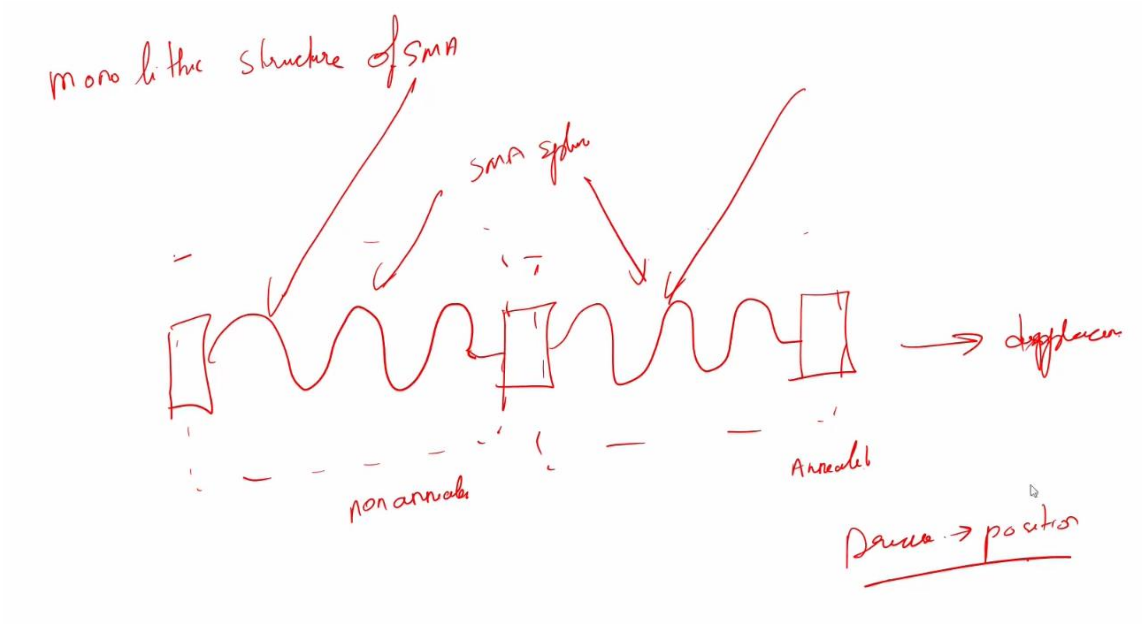
When we try to cut off the heat, it returns to its shape. In fact, just to give you a better understanding, let me show you the overall mechanism of stress generation when a shape memory alloy is deposited on a silicon wafer. So let us consider that there will be a different phase regime which exhibits this kind of martensite behavior. So, if I try to map it with reference to the stress and with reference to temperature, this is the sigma max and sigma d. We have the martensite phase over here. This is a kind of phase transformation regime, and this is the bimorph recline, and this is the austenite phase.

We have annealing, and this is the temperature for annealing. And this is the kind of crystalline material that exhibits. So when we try to illustrate this figure, this is a kind of NiTi film that is deposited on an SI substrate. At the deposit temperature considered, the film is amorphous; no crystallographic structure is formed. To be functional, an annealing step is required, which is realized by heating the film typically to 700 to 900 degrees Kelvin; upon heating, due to the difference between this transformation film and the substrate, a compressive stress builds up. So, upon crystallization at a temperature Ta, the stress is relaxed and the film is under tensile stress on cooling.

So, in the device operating mode, the biasing stress can be effectively used to deflect, for instance, an SI cantilever beam or a membrane. So this can be used for a kind of micro gripper arrangement. For example, if this is a kind of micro gripper arrangement and here we have a bimorph structure. So what happens is the actuation can be appropriately like we can give a biasing appropriately to get the required actuation.

So that is one advantage of this system. So we can encash a kind of one-way effect and then we can create a kind of appropriate displacement using this structure. The next concept is kind of a two-way effect. In the case of a two-way effect, we have a monolithic structure. So it is something like this: you have a single structure; one way of actuation is happening in this direction, and the second way is happening in this direction.

This kind of two-way effect can be effectively used or deployed using this system. In addition to this, there is one more design principle available, which we call a kind of monolithic base structure. This will also deploy a similar concept in the case of a monolithic structure; what happens is that we are using a single system, and these single systems are appropriately fabricated to achieve the structure. So the actuating properties of the SMA originate particularly from the crystallographic transformation that takes place when the temperature is varied. So, the crystallographic transformation can only occur if the material is crystallized. So, the crystallization of the material is achieved by heating the material at high temperatures, typically in the range of 500 to 800 degrees Celsius after the forming process.



If the annealing step is not conducted, proper crystallization will not be present, and consequently, the material will not exhibit shape memory properties; instead, it will behave like a conventional metallic material. So when we look into the concept of this monolithic integration in SMA, it consists of performing the annealing step only locally rather than in the complete device volume and using the combination of the annealed and the non-annealed zones to perform the attrition functions. It is something like this, assuming we have only one or two springs, for example, in the case of a monolithic structure of SMA. Let us consider that this is a kind of annealed structure and this is a kind of non-annealed structure.

So, this is a kind of SMA spline structure. So, we are manipulating the crystallization appropriately to get the required displacement. In fact, higher order in order to take care of the precise control, here the actuation is through thermal means. We can also use a laser. So when we try to irradiate the system with the laser appropriately, we can achieve a precise position. These are some kinds of configurations that are available for creating these monolithic structures for SME-related applications.

Of course, there are wide combinations of various configurations of SMEs that can be effectively used for micro-robotic related applications, which we have seen and will be seeing in biomimicking as well as in other robotic structures.