Microrobotics

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Week- 05

Lecture No- 21

Microactuation and Micromanipulation - Module 06

In this module, we will discuss microactuation and micromanipulation under the course on microrobotics. In that, we will be discussing shape memory alloys, conducting polymer-based actuations, stick-slip mechanisms, and comb drive actuators. Firstly, discuss shape memory alloys (SMAs), as they fall under the category of smart materials. Compared to the other materials, smart materials have a certain amount of specific advantages; in fact, they have a specialized functionality in such a way that they can be used for specific applications. These smart materials have potential applications in the case of these bio-mimicking robots, because in that case, they don't follow the conventional degrees of freedom. If it follows the conventional degrees of freedom, motors are used as actuators for the conventional degrees of freedom.

However, in this particular case, when going for a kind of smart material-based structures, you can mimic and program the materials for a biomimicking-related application. This is one of the advantages of going for these smart material-based structures. Now, look into the overall requirements of these smart materials. When trying to integrate these smart materials, they should have the capability to interface with the sensor, and they should have the capability to interface with the controller.

This smart material should have a good handhold with the sensors and the control system to form a smart system. These smart systems are utilized quite efficiently in such a way that they can be used for different specialized functional applications, for example, SMA-based micro robots. These shape memory alloy-based micro robots can walk or generate micron steps, possibly using this particular system or arrangement. So, whenever trying to develop such kinds of smart material-based structures, it may be necessary to integrate them with sensors. Therefore, it should have the capability to integrate well with sensors and controllers.

However, there are certain cases where the smart material itself can act as a sensor as well as an actuator. The brief overview of the family of smart materials includes a list of smart materials that are available, which includes SME, piezo, hydrogels, ferrofluid, conducting

polymers, thermoresponsive polymers, and pneumatic-based flexible materials. Many such kinds of smart materials are available, and these have potential applications in micro-robotic related applications as well as in their characteristics. When trying to discuss the family of these materials, one question that comes to mind is how we select a particular material or actuator for a specific application. We may need to consider two important parameters.

One parameter is called actuation stress and the other is actuation strain. Actuation stress is nothing but the amount of load applied to it, and appropriately, the amount of strain that is displaced from it is determined. This is based on the actuation stress and actuation strain, as well as the requirement. So when we consider smart material-based actuators, and if we need to select an actuator for a particular application, then the actuation stress is decided based on the actuation stress and actuation strain. In addition to this, it depends on the responsiveness of the material and the overall frequency of actuation of the material.
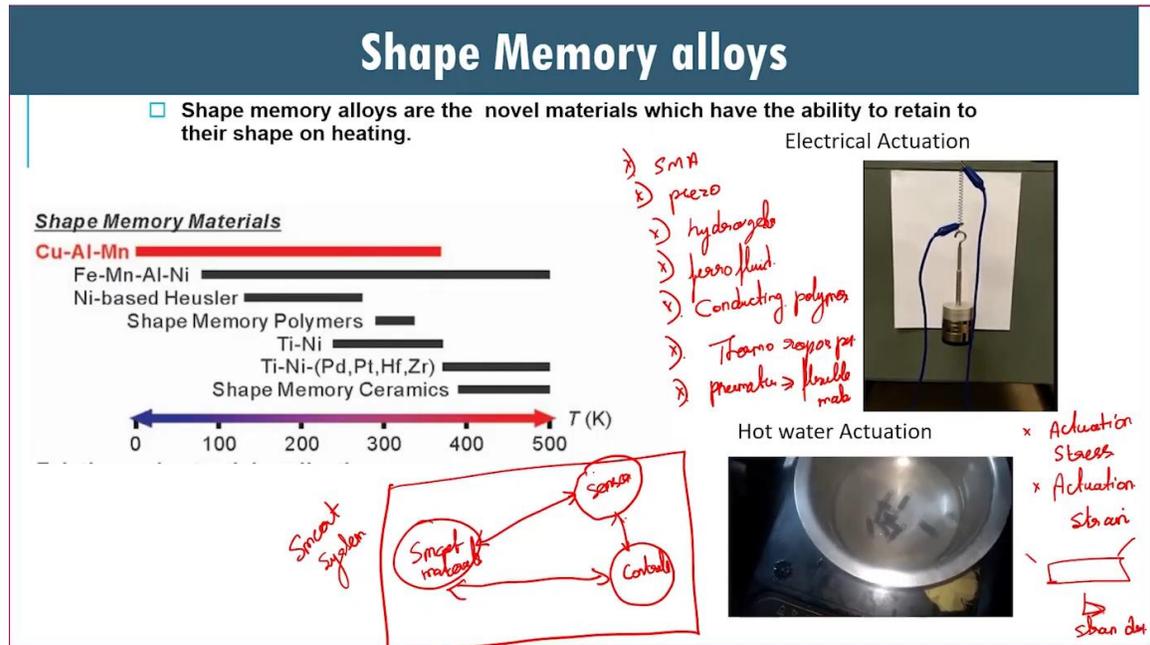

It also depends on the overall resolution of the material; the reliability and repeatability of the actuator are also considered key parameters for selecting a certain amount of smart material for smart material-based actuator applications. Now, in addition to this, there is one more parameter, which can be energy density, and another important parameter is hysteresis. Hysteresis can also be considered one of the key parameters that will create an impact on smart materials, or it can also be considered a designing parameter with reference to functionality and applications. Shape memory alloys are the materials which are responsive to heat. One more characteristic that also decides is the actuation medium.

The actuation medium, as in the case of SMA, is thermal. In certain cases, it is electrically based; that is, in the case of piezo, it is electrically based. In the case of Magnetostrictive

materials, it has a magnetic base. In certain cases, like conducting polymers, ionic polymers, or thermoresponsive polymers, these are electricity-based. In some cases, certain materials are responsive to moisture content, such as microbubble structures.

Take a small tissue paper and let us consider that you have a cup of hot water. So, when you try to put the tissue paper on top of it, either the tissue paper falls or the tissue paper tries to fall inside the cup of water. This is because, like whatever steam is being generated, the steam will start filling up these microbubbles. These microbubbles get enlarged, and finally, there will be an increase in density; because of this, the paper will try to fall into the liquid and become synchronized. So these are called micro-bubble structures, and the overall medium is the moisture medium.
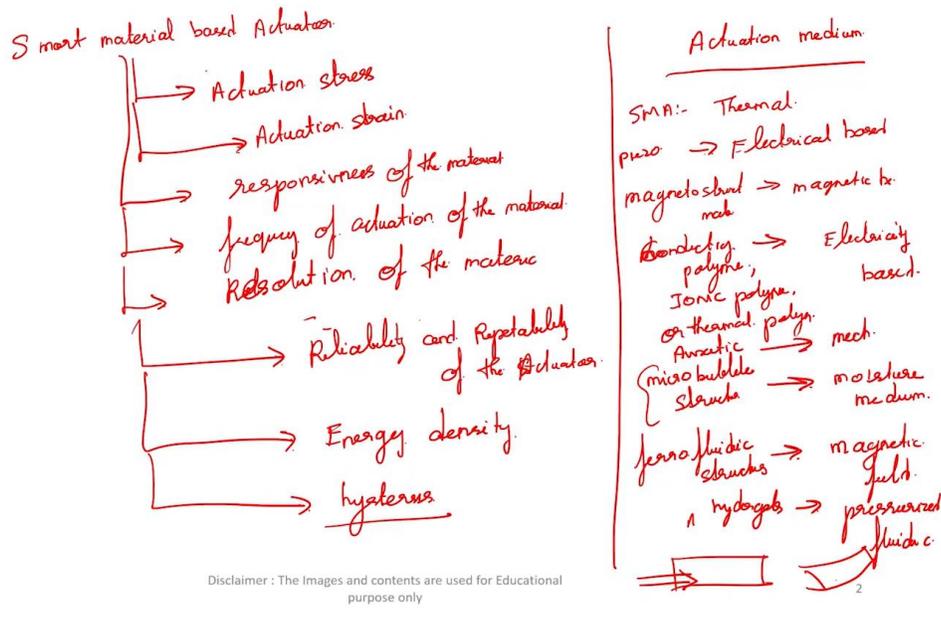
There is a concept called ferrofluidic structures. These ferrofluidic structures have a kind of magnetorheological-based particles used to collect the magnetic nanoparticles and mix them in a liquid medium or sometimes in a gel medium as well. Then, they try to align a magnetic field surrounding the surface so that spikes come out of it. Such ferrofluidic structures are basically actuated or manipulated using a magnetic field, and then we have the hydrogels, which are actuated using a pressurized fluid. Hydrogels will have a kind of structure through which, when we try to inject it, it creates an impact.

Additionally, we have an auxetic structure, where mechanical loading is considered to be one of the key elements of this auxetic structure. Now, let us discuss the functionality of a shape memory alloy; these are responsive to heat. This video will give you clarity. Here, there is a shape memory alloy spring. This shape memory alloy spring is attached to a weight.

When it is attached to the weight, a kind of expansion is observed, and when you try to give it an electrical bias, it returns to its shape. Similarly, this material is highly responsive to heat. Similarly, in another video, the person is trying to have a spring, and he is trying to elongate the spring by putting those elongated springs in hot water, and you can see it is highly responsive to heat; it is trying to take shape and forms a kind of structure. Now, one of the key aspects that may need to be looked into is SMA; input in terms of deformation and actuation is through heat, and the output we get is in terms of displacement. So, if you keenly observe this, the amount of displacement can be efficiently controlled based on the electrical bias.

That is, let us consider that we are just enlarging the shape memory alloy and trying to give it a kind of energy. It is completely in an elongated phase, and then when I try to supply heat, it will attempt to return to its original state. Now the position at which it needs to come back can be appropriately restricted by applying an electrical bias to this particular system. In case if I try to give a pulsed current then appropriately I can have a control over the electrical biasing, this is one advantage of this system. Conventionally, you can use a conventional heat source, or in some cases, you can also apply an electrical bias to appropriately constrain the requirements we are looking for.
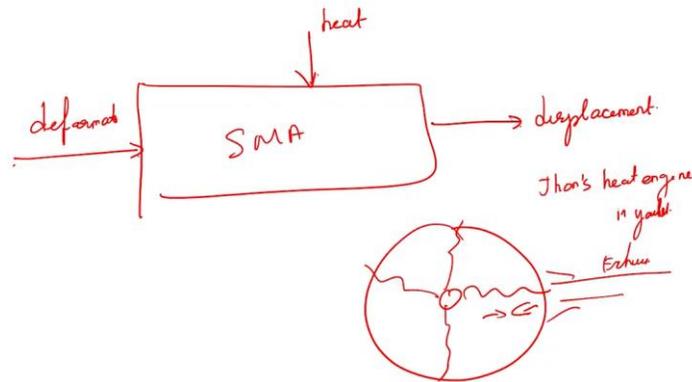
In fact, one of the applications we performed some experiments on was the development of a kind of shape memory alloy-based engine, which is called Johnson's heat engine. The main aspect of the Johnson heat engine is that it will have a kind of rim with shape memory alloy springs integrated into it. We kept this ring near the exhaust of a vehicle. So, what happens is there was a kind of contraction and elongation in these particular springs, which resulted in a kind of rotation. You can refer to Johnson's heat engine on YouTube; you will find a lot of videos on this.

In fact, this is a kind of rotation that happens because of the shift in the center of gravity when these kinds of smart material-based structures are integrated. Now, let us see the overall family of smart materials, and here, based on the type of actuation, we try to select the shape memory alloys according to our requirements. Ideally, these shape memory alloys are classified based on the actuation temperature. If you are considering it for an actuator application or based on the sensing window, consider it for a sensor. Now, there are different types of shape memory alloy materials.

One is a copper-based shape memory alloy, which has a combination of Cu-Al-Mn or Cu-Al-Mn-Zn, etc. It might be either a ternary or a quaternary alloy. Then there are some Fe-Mn-Al-Ni based combinations, and there are Ni-based Heusler alloys. Heusler alloys are basically referred to as magnetic shape memory alloys. Then quite a good amount of shape memory alloy polymers is available, and we have a nickel-titanium-based shape memory alloy and nickel titanium integrated with certain intermetallics, which include Pd, Pt, Hf, and zirconium-based structures so that it can be appropriately used for manipulating the structures.
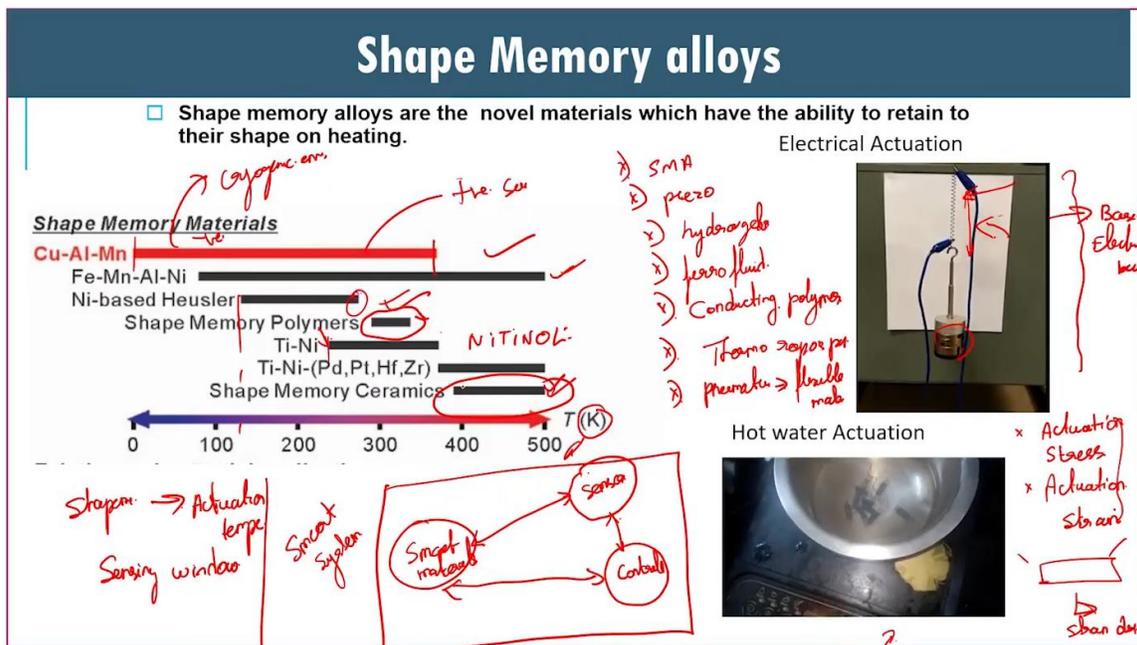
Then there are shape memory alloy ceramics. Many shape memory ceramics are being developed primarily for high-temperature applications, etc. Now, if you see the overall family of these shape memory alloys, this family of shape memory alloys is governed by the actuation temperature. So, if you see in this particular case, this is with reference to Kelvin, the case of copper-based shape memory alloy, you have a wider spectrum. This works on both the positive side as well as the negative.

That is, it has the capability to work in a cryogenic environment also. This is one advantage of these copper-based shape memory alloys. Like you can work on liquid hydrogen, liquid

helium, liquid oxygen, liquid nitrogen, and so on, in all these domains, these shape memory alloys can be actuated, and they also have potential applications up to 250 to 350 degrees Celsius. The working window, which is the mechanism of shifting and transition, changes with reference to different compulsions. It has a complete alloy diagram, which discusses the composition diagram and its influence with reference to different temperatures.

Then we have an Fe-Mn-Al-Ni alloy, which has a wide spectrum. However, from a life cycle and fatigue perspective, it has its own limitations. So commercially, not many Fe-Mn-Al-Ni alloys are available. Many people work closely on copper-based shape memory alloys. In fact, quite a good amount of research has been performed in this particular domain.

Then we have the Ni-based Heusler alloys. These Ni-based Heusler alloys are also capable of working in the low temperature domain and slightly in the high temperature domain, but they are mainly more suited for the low temperature domain. Then we have the shape memory alloy polymers. These are widely used in soft robotics-related applications, especially for gripper-related applications, and in certain cases, they are also used for actuation-related applications, and used for switches, switching-related applications, etc. However, since their working window is limited, they have their own limitations regarding applications.

Then we have NiTi structures. These are considered to be conventionally available structures. These nickel-titanium structures, if you try to procure a shape memory alloy, are mostly nickel-titanium structures. In fact, under a brand name, it is called Nitinol, which is commercially available in the market, and it has quite a good amount of working window. From the cryogenic perspective, it has very good properties in the case of a liquid nitrogen environment. From a high-temperature perspective, it has very good properties in the range of 80 to 130 degrees Celsius.

Then there are several research groups that have attempted to add a certain amount of intermetallic structures and intermetallic layers, including Pd, Pt, Hf, and zirconium-based structures, to these nickel-titanium-based structures so that we can appropriately tune the properties of the shape memory alloy and make it workable for the customized environment or the customer's characteristics. Next is with respect to shape memory ceramics; this is quite a challenging area. Not much work is there in this particular domain. In fact, from a micro robotics perspective, this is not much explored. However, there are some possibilities because whenever we are working under high-temperature conditions, these ceramics can probably be deployed.
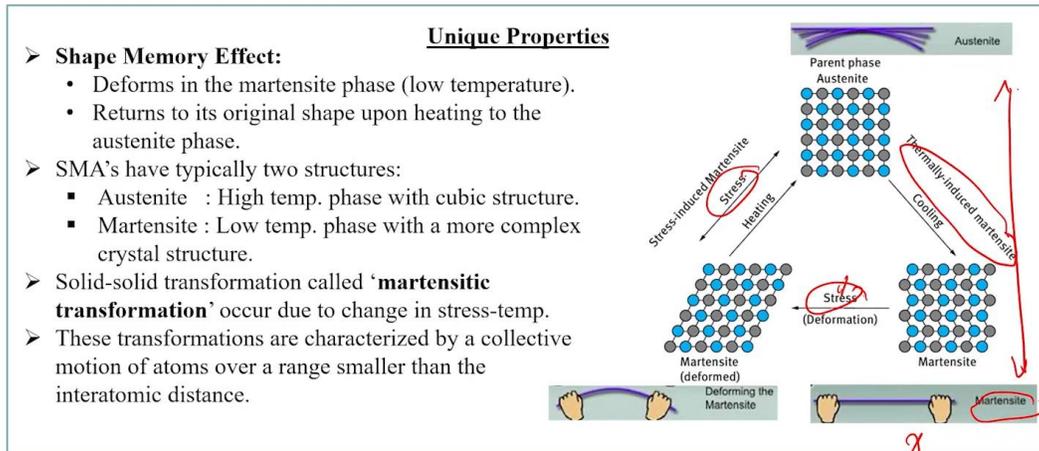
In fact, that is the reason most of the working window is in the range of completely close to around 400 to 500 K, which means it has a positive domain. However, it doesn't have any kind of functionality in the case of a cryogenic system or any kind of low-temperature

conditions, etc. Now, these are a family of shape-memory alloys. What makes this shape memory alloy capable of falling under the category of smart materials for developing different smart systems? Now, as far as shape memory alloys are concerned, we need to understand the history of shape memory alloys. So, in fact, the first shape memory effect was demonstrated in the gold-cadmium materials and gold-cadmium alloys, where it exhibited a kind of pseudo-elastic behavior.

The first SMA characteristics were demonstrated in 1932. Then later, William Beuchler and Frederick developed nickel titanium alloys for the Naval Ordnance Lab from 1962 to 1963. This is exactly the point at which nitinol came into existence. In fact, since it is called the Naval Ordnance Lab, this nitinol is derived from this lab. From this particular point, the shape memory alloys are considered to be a kind of strategically driven material because they have potential applications towards biomimicking related structures for maneuvering aircraft.

In fact, smart aerofoil structures can be demonstrated and developed using this particular shape memory alloy integrated system. There are some systems where small micro walls and micro transducers have also been developed using shape memory alloy structures. Now, with reference to the biomedical perspective, since the shape memory alloy comprises nickel and titanium, these nickel and titanium structures are highly biocompatible. They can be effectively used for certain biocompatibility-related applications. One of the applications, such as shape memory alloy-based pins and shape memory alloy-based braces, is an example of where it has been effectively used for biocompatible-related applications. Most of you might have heard about the shape memory alloy-based stents, which are incorporated inside the walls as well as inside the tubes. Such shape memory alloy stents can also be applied. Now, as I had mentioned, one is used for aerospace and another is with respect to biomedical devices. However, with respect to the micro-robotics perspective, it has the capability to be manufactured at a micron level, and then the actuation can be done through external means so that it can be appropriately opened up. In fact, there are reports on shape memory alloy-based micro robots, which are used for a certain number of surgical applications, which we'll be discussing in the upcoming models.

Shape Memory Alloy

Unique Properties

> **Shape Memory Effect:**
> - Deforms in the martensite phase (low temperature).
> - Returns to its original shape upon heating to the austenite phase.
>
> SMA's have typically two structures:
> - Austenite : High temp. phase with cubic structure.
> - Martensite : Low temp. phase with a more complex crystal structure.
>
> Solid-solid transformation called '**martensitic transformation**' occur due to change in stress-temp.
>
> These transformations are characterized by a collective motion of atoms over a range smaller than the interatomic distance.

Now, what makes shape memory alloy capable enough to retain its functionality. Now, if you try to look into the fundamentals behind this structure, it basically happens because of the switching between the austenite phase and the martensite phase. Let us consider that I have a rod made of shape memory alloy. Now, this rod made of shape memory alloy is initially in a martensite phase, as shown over here. Now, what I am trying to do is deform this rod, which I call a deformed martensite. So, I am applying stress to this rod to form deformed martensite. From the deformed martensite, when I try to supply heat to it, it transforms into an austenite phase, which is referred to as the parent phase. Now, upon cooling it, due to the thermally induced martensite, it returns to the martensite phase. This is a kind of cycle that is a well-established key fundamental behind the shape memory alloy-based structure. If you closely observe the overall characteristics, stress is involved, thermally induced martensite is involved, and again, stress is involved.

So, it's a kind of thermo-mechanical effect, as I would say, where a thermal effect and a mechanical effect are separately induced to achieve the required transformation and actuation we are looking for. Now, as far as we try to look into these fundamentals, there is a kind of transition phase that is exhibited in all these domains. So this transition phase plays a vital role with reference to the actuation and with reference to the response time of the sensor. For example, if I want to use it instantaneously, it might be very difficult. That is the reason some shape memory alloys are highly restricted to a low frequency; for example, the maximum frequency a shape memory alloy can exert is around 10 to 15 hertz. However, from an energy density perspective, it has a good amount of applications as well as a good amount of characteristics. How these shape memory alloys can be developed, how these shape memory alloys can be trained, and how these shape memory alloys are being effectively used for a robotic application, let us discuss in the upcoming classes.