Foundations of Cognitive Robotics
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Lecture – 03

In the last class, we have talked about one of the basic building blocks for organismoid robots, which is piezoelectric smart material. We have discussed how this piezoelectric smart material, with the help of the direct and the reverse effects, can build up different types of actuators and sensors, which can be very effective in terms of developing some of the parts of these robots.

Now, there are certain disadvantages of these piezoelectric materials; one, of course, is that it needs slightly high voltage and secondly, it is basically a kind of a capacitor in nature. So, just like a capacitor gets discharged with respect to time; similarly, piezoelectric material loses its efficiency because it gets discharged, and hence, it needs to be reported after particular durations of time.

So, it can be used for a very sophisticated type of action, let us say for the finger manipulations or for certain motions or rotations, but for more robust and rugged action, we need more powerful actuators. Now, one of the most powerful actuators is the magnetostrictive actuator. Also, we will talk about some of the artificial muscles that we can develop with the help of another smart material called shape memory alloy. So, let us have a look into both of these different these two different types of smart materials; the magnetostrictive materials and the shape memory alloy.

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We will first talk about the magnetostrictive materials, and the name itself is somewhat suggesting to you that these are materials which have a magnetic connection. Yes, indeed, that these are materials that respond to the change in the magnetic field.

So, whenever at the advantage of the magnetic field is that you can essentially generate the changes without physically in touch with the object, which means you can develop the force at a distance because the magnetic field can get transferred without physical contact. So, that is the attractive part of it, and the second part the *strictive* part to magnetostrictive materials; it essentially refers to that the magnetostrictive material can respond with the change in the magnetic field, and that is what is the *strictive* refers to.

Now, if we look into the availability of magnetostrictive materials, we will see that one of the most popular magnetostrictive material is Terfenol - D, which is made of rare earth material called Terbium and Iron that is the Fe and it is first developed in Naval Ordinance Laboratory.

So, that is why their name goes, and of course, there is a D that stands for Dysprosium. So, essentially, it is a kind of an alloy of terbium iron and Dysprosium. Now, what it imparts this alloy is a very high energy density.

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If you can look at this video of a Terfenol - D material sample here and you can see that if it is hit, you know just impact was so much of energy gets dissipated from the system. So, it has a very high energy density. Now, naturally, these actually tells us that it will be very good in terms of an actuator.

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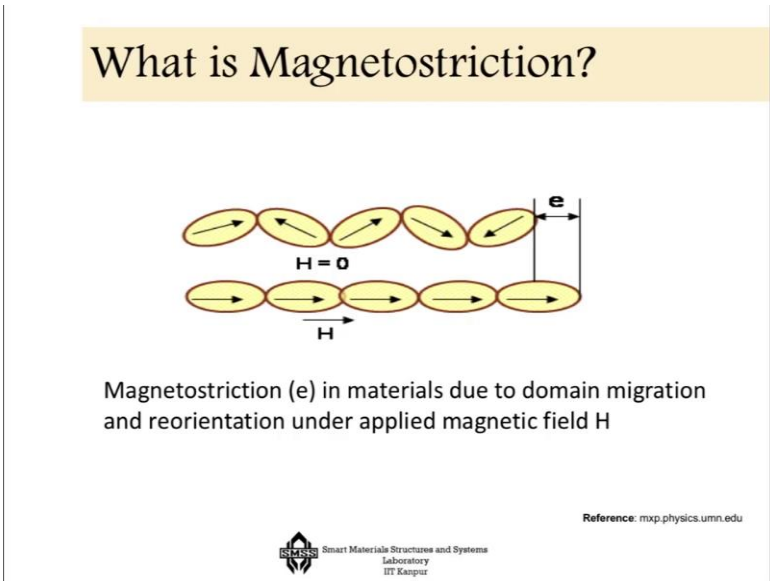

Now, how does this magnetostriction happens in these kinds of materials? Well, you can think of that as if each of these magnetostrictive elements will be having millions of this type of small magnetic domains just like beads, with its own, you know dipole direction, with its own magnetic field directions which can be random, to begin with. So, that is what is the general state of magnetostrictive material when the magnetic field applied is 0.

Now, the moment from a distance, I apply a magnetic field. Each one of these magnetic domains they starts to align themselves with the magnetic field, and you can see. As a result, the entire group of materials they expand in one direction, creating one magnetostriction in the system.

So thus, by applying a magnetic field, it can actually expand, but by playing certain tricks, you can also make it contract, and thus, you can make a forward and backward movement with the help of the magnetic field by using this type of a system.

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Some Magnetostrictive Materials

Material	Magnetostriction (ppm)	Curie Temp (K)
Fe	14	633
Ni	-33	1043
Co	50	350
Permalloy	27	713
$DyFe_2$	650	635
$TbFe_2$	2630	703
$Tb_{.3}Dy_{.7}Fe_{1.9}$	2400	653

Smart Materials Structures and Systems Laboratory
IIT Kanpur

Now, there are a whole lot of materials ferromagnetic materials, mostly which show this behavior, and its initially it was observed, of course, in iron and nickel by Joule long before in 1880.

But today, the material, as I already told you, we use one of them is terbium dysprosium and iron and also, there is another material in which instead of terbium, we use gallium actually. So, these materials have large magnetostriction; that means, you know they show large deformation in comparison to let us say iron or nickel. So, something like 2400 parts per million that is the level of strain that you will see.

Now, this is, of course, a dimensionless quantity, and the other important thing is that it will show these two up to a very high temperature, which is good means they can really work in a very rugged environment. Now, how much is this 2400 or 2500 parts per million, it is even though you know it looks like a large number; but in terms of actual change of length, it is not that large.

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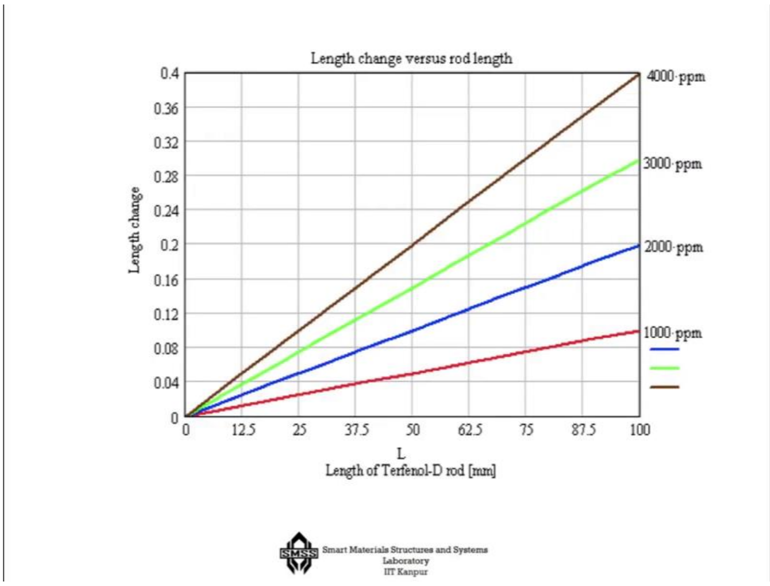

In fact, if you look at this curve that we have here the length of Terfenol - D rod, let us say we consider a 100-millimeter length rod, then with about 2500 parts per million, the change will happen is only 0.24 millimeter. So, which is even smaller than 1 millimeter. It may not be visible by the naked eye. But it actually has a lot of power, and you can also amplify just like for piezoelectric material and then, you know you can make good use of this kind of system.

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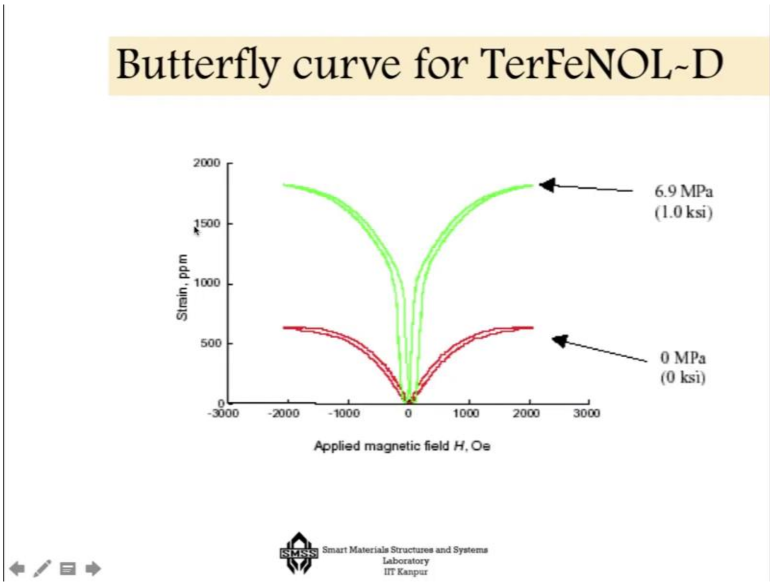

So, the other important thing for the Terfenol - D material is, as I told you, that if I change the direction of the magnetic field, no matter positive or negative, you will always get expansion out of it. It always increases.

But there are two interesting things to note here that if you can somehow keep us keep it stress, to begin with, you apply some initial stress, you can get actually larger strain out of the system and the second thing is that this is how you can a get a bi-directional movement. Let us say if you keep it already under a biased magnetic field, let us say somewhere here; then, if you increase the magnetic field, it is going to expand; if you decrease, it is going to come down.

So, which means you can actually get a bi-directional movement out of the whole thing. The only thing that you are sacrificing is that the range of strain in the earlier case, if it is only unidirectional, is quite large; whereas, here, it will be with respect to the bias, and here is that range will be smaller. It will be about half of what you can get otherwise. So, this is what is the famous butterfly curve that one has to keep in mind for designing systems using Terfenol - D.

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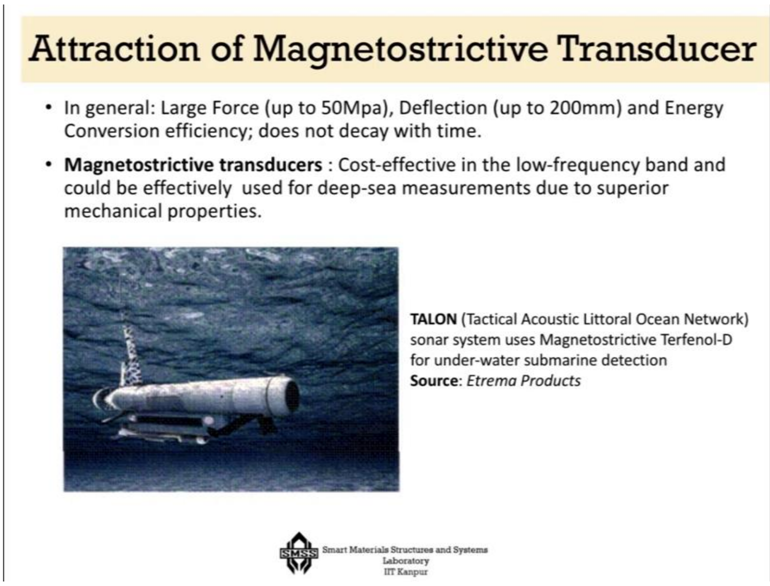

Now, the attraction of such Terfenol - D material is manifold. For example, you can use it for large force generation up to 50 MPa stress levels you can create. You can create large deflection up to 200 millimeters, and you can get a large energy conversion efficiency and most importantly, it does not decay with the time that is a very good advantage of the magnetostrictive transducer.

And it is cost-effective in terms of a low-frequency band, it is not as high as a frequency band like a piezoelectric material and firstly, it was used in deep-sea underwater applications like this TALON you can see Tactical Acoustic Littoral Ocean Network, the entire sonar system of TALON is made out of magnetostrictive Terfenol - D materials which is sourced by Etrema products.

Now, I told you about direct and reverse effects if you remember. The direct effect is useful as a sensor. When you are applying force, you can get the voltage or in this case, a change of magnetization, in a magnetostrictive material that is the direct effect and the reverse effect is used for the development of actuators, wherein this case as you will be changing the magnetic field, we will be able to see the change in terms of the length of the system.

Now, for magnetostrictive material, there are many different effects you need not only always see the change in length. You can actually generate the change in terms of twisting in the system or a change in terms of the bulk volume in the system. And similarly, the same material can respond to if there is a twisting happening or if there is a bulk change of volume that is happening, it can respond to that through the change concerning the change in magnetization. So, there are various effects of the magnetostrictive material.

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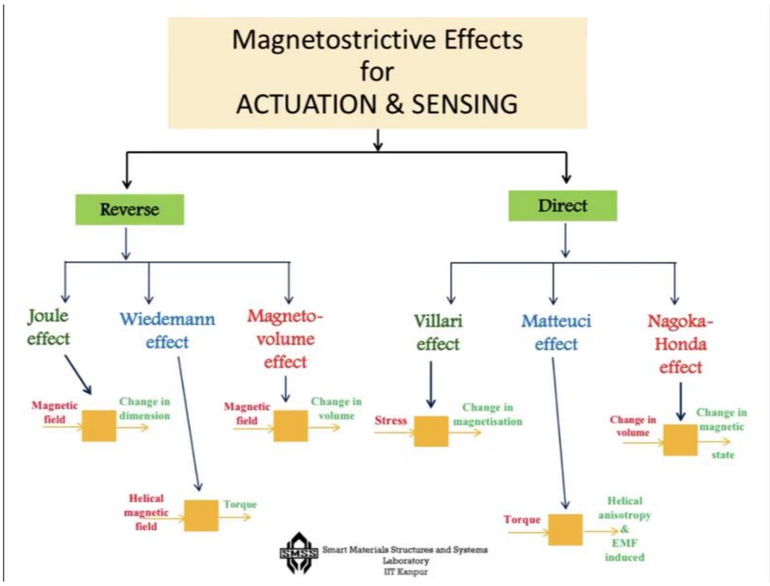

Some of the magnetostrictive effects which are used for actuation and sensing are for the reverse effect joule effect is, of course there, where there is a change in dimension. But also sometimes, we use the Wiedemann effect, where a helical magnetic field will create a torque so that if you have a torque like you know motion generation system required, you can use the Wiedemann effect.

And also, in some other cases, you can use the Magneto volume effect so that the magnetic field can create a change in volume. And from the sensor perspective, there is the Villari effect, which responds to the change of stress and in the axial direction, and that is reflected in terms of change in magnetostriction.

But there is also the Matteucci effect, where if there is a torque, it senses, and it changes in terms of a kind of a magnetic field induced EMF, and there is something which is known as Nagaoka Honda effect, where if there is a change in volume, it actually senses heat in terms of a change in magnetic state. So, there are three varieties of reverse effects and three varieties of direct effect which you can use for building up actuators and sensors using magnetostrictive material.

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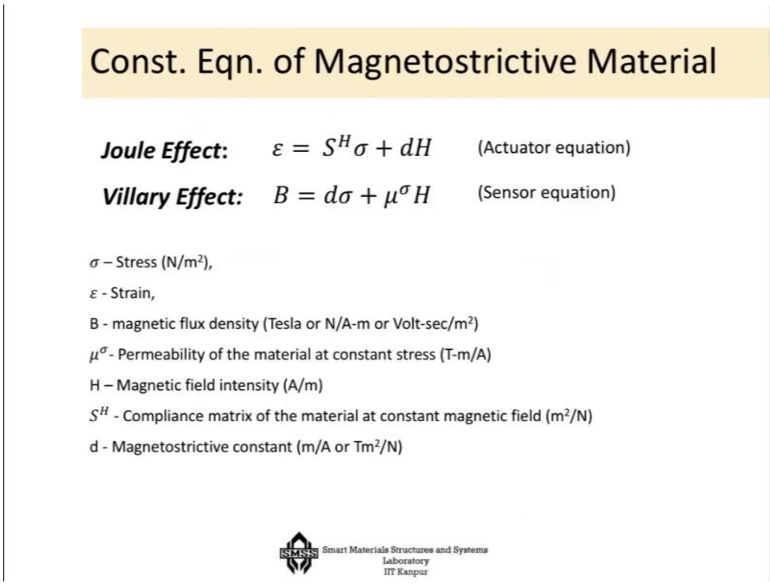

Now, the constitutive equation of such materials is actually very similar to the piezoelectric material. As you can see that for the actuators point of view, we generally use the Joule effect, and in the Joule effect, if you apply the magnetic field through H, you will be able to see the strain, and that is the deformation, and that is the deformation that we can use in terms of either by restricting it.

So, that you get a force or by a change of length of the system. Remember if there is a change of stress, then also deformation occurs, but that is not like a smart material like behavior because that happens for any system.

For the magnetostrictive material, this actually happens because of once again the coupling called magneto-mechanical coupling here like piezoelectric coupling. So, here this *d* creates a coupling between H and ε. So, that if there is a change in H, you get a change in ε.

Now, that is as far as the actuator building is concerned. Similarly, for the Villary effect, if there is a change in stress sigma, then there will be a change in magnetization, which can be sensed in terms of a change of voltage in a pickup coil and once again, the magneto-mechanical constant d plays an important role here because as the d increases for a material with a smaller change of stress, you will be able to get a large change of magnetization.

Of course, the magnetization can be changed by the magnetic field also, but that is something that happens for the regular solenoid, and it is governed by permeability, and that is not what we are focusing on a smart material. It is this d sigma part which we will be capitalizing on for the development of the sensors for the magnetostrictive material. Now, there are many applications of it.

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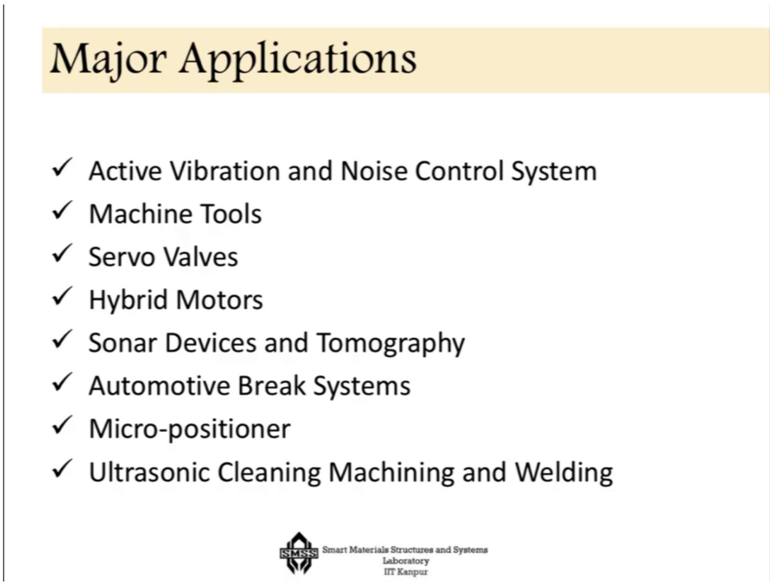

For example, if you want to control the noise and vibration, let us say during the motion of a robot, this is used. Machine tools, if you have control of machine tools. Controlling of servo valves just like I told you that. So, many servo valves are required, for example, the different types of pneumatic actuation.

So, you can actually use these magnetostrictive materials instead of you know compression based pneumatic materials; it will be much less bulky. So, for servo valves, you can use it. You can use it for hybrid motors, for Sonar devices, for brake systems, micro-positioner, and different types of cleaning and welding type of applications.

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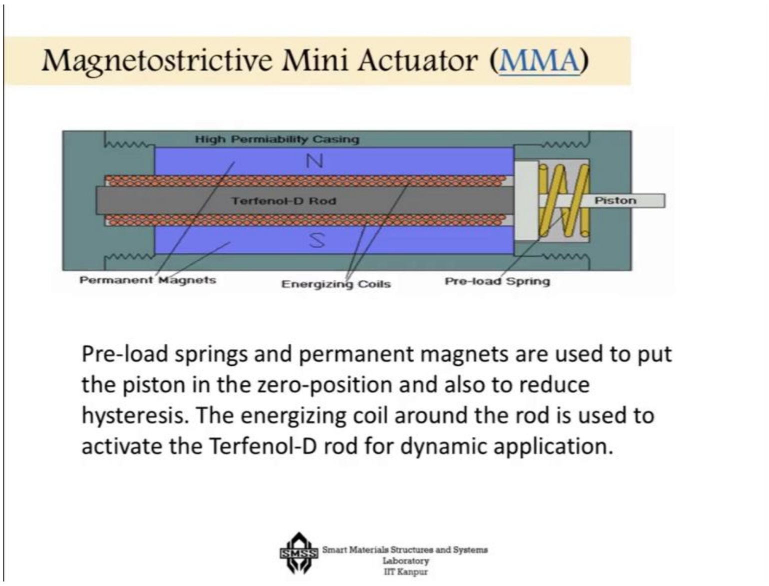

Now, one of the very common magnetostrictive actuators is called mini magnetostrictive actuator. So, if you look at this mini magnetostrictive actuator, in this case, you can see that there is a Terfenol - D rod which is sitting inside as you can see it here and then, there are this magnetization coils and there is a set of a permanent magnet.

So, what will happen is that the moment I will apply, and because of this, permanent magnets are already biased. Now, the moment I will apply an external magnetic field, then depending on the direction of it, this Terfenol - D rod will expand or contract and as a result, this piston will move forward and backward, and that can be used in terms of motion generation in a robot for various types of applications.

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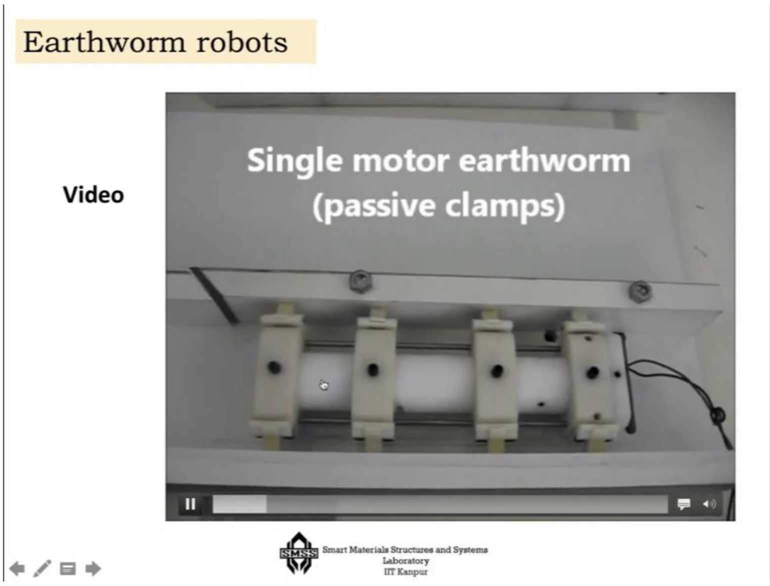

Now, here I will show you a fascinating application of magnetostrictive material, and this is in terms of its motion as an earthworm in a conduit. So, you can see this is also known as inchworm motion and there are you know inside, these there are these magnetostrictive materials, and there is a stick-slip happening.

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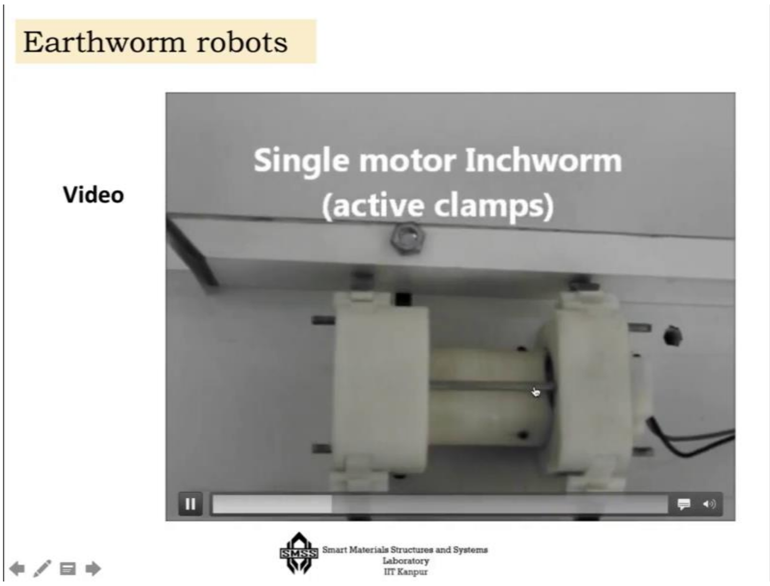

And because of the expansion and contractions and you can see that you know that is happening and that is creating, these stick slips and the whole thing is actually propagating.

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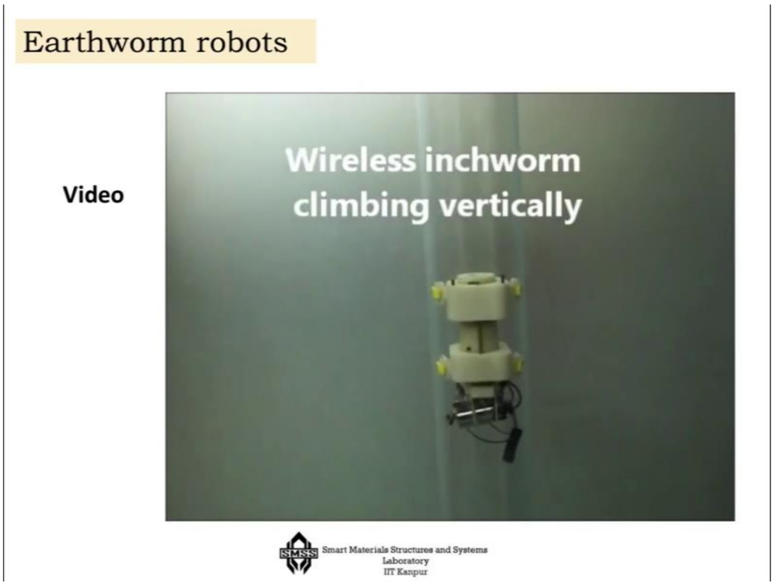

So, you can make it wired or wireless, but this has excellent applications in terms of the development of pipe health monitoring robots, and you see this is an application that is entirely wireless, and you see the whole thing is moving vertically.

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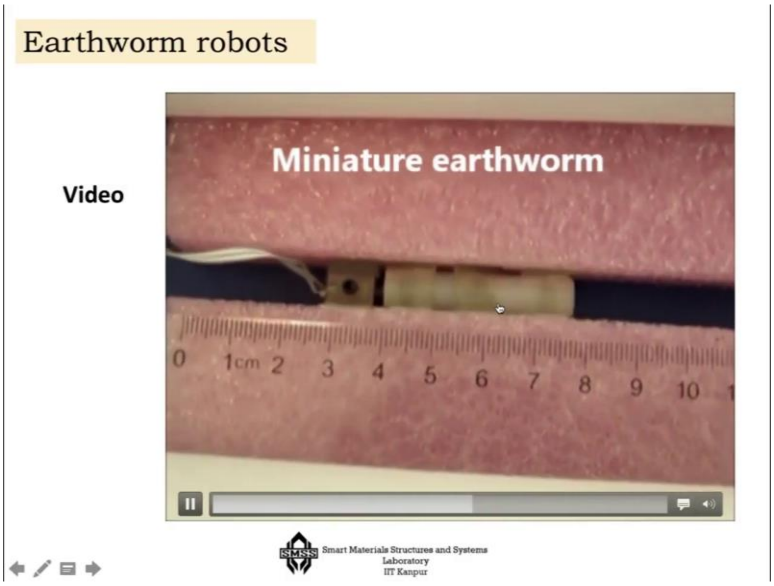

So, if you want to let us say create an animalistic motion, let us say a kind of an ant-like motor which are actually miniature, as you can see here, particularly in miniaturized circuitry.

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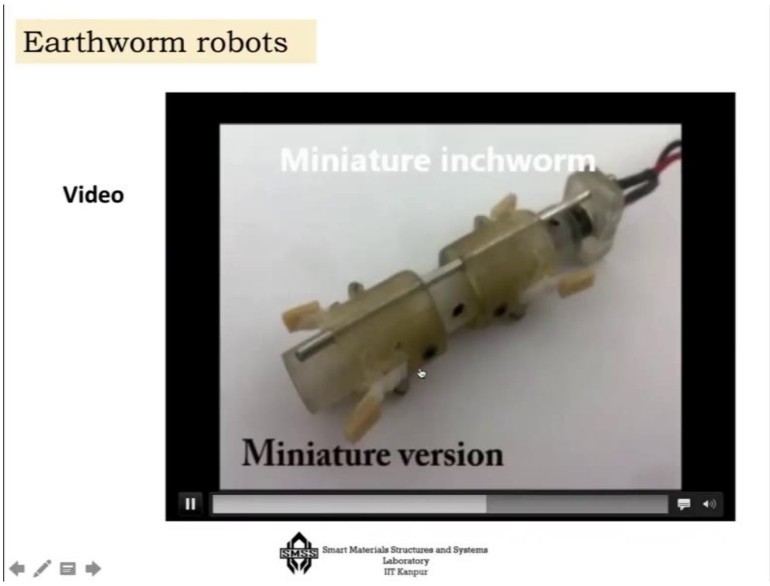

So, an ant-like motor and inside a conduit, this particular type of robot is in magnetostrictive actuator can be very good in terms of generation of such motions as you can see that how small you can make the whole thing.

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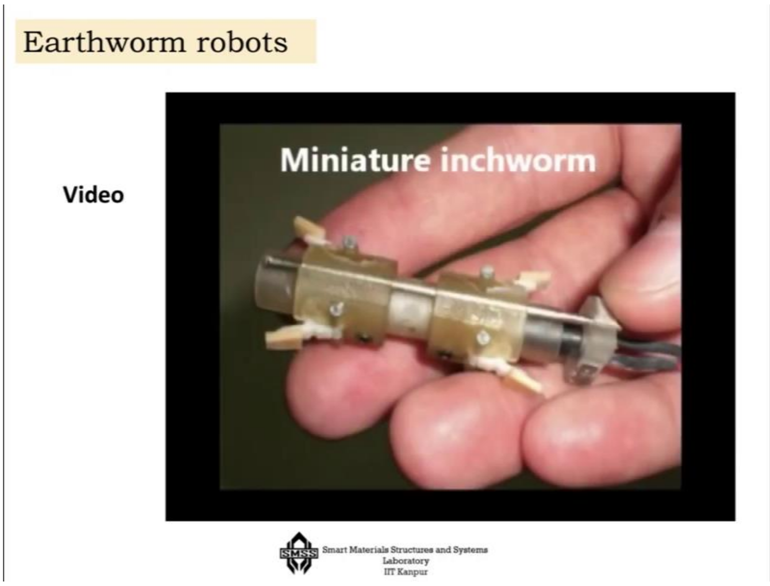

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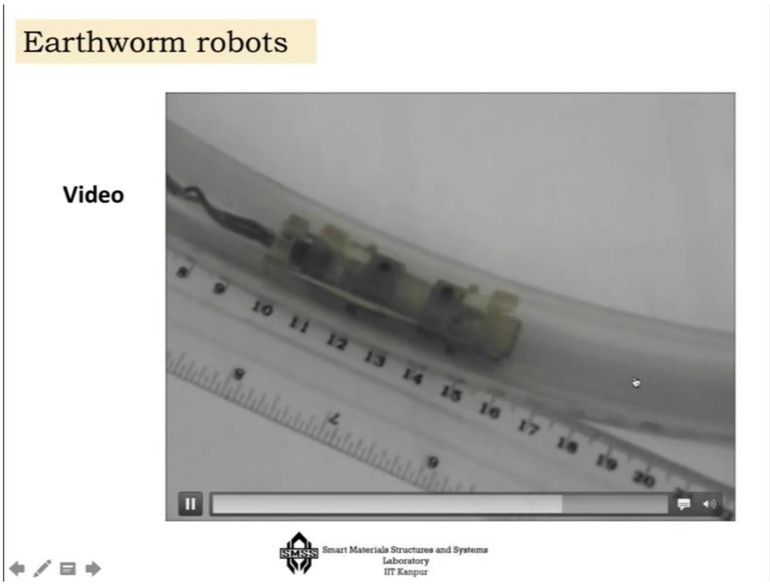

And here, you can see that how nicely it is going inside a pipe, and if you have sensors, it can actually monitor, in that case, the nature of changes that are happening in the pipe, and it can do that both upward and downward.

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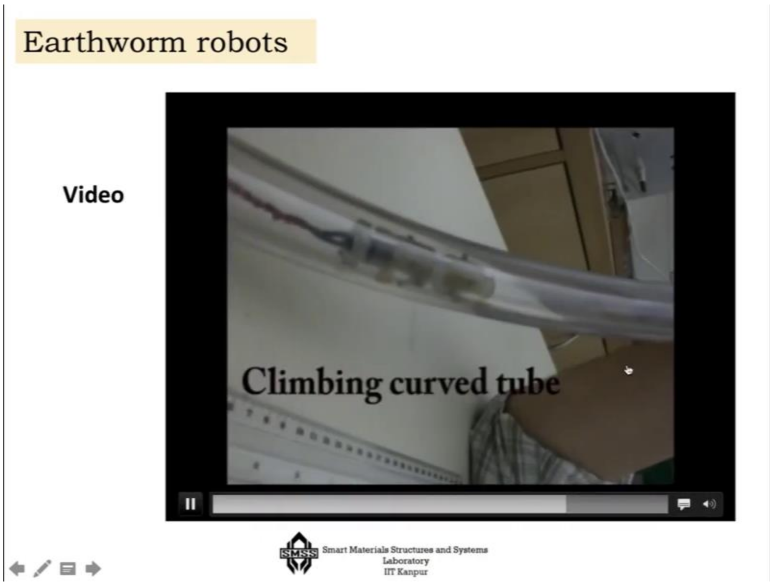

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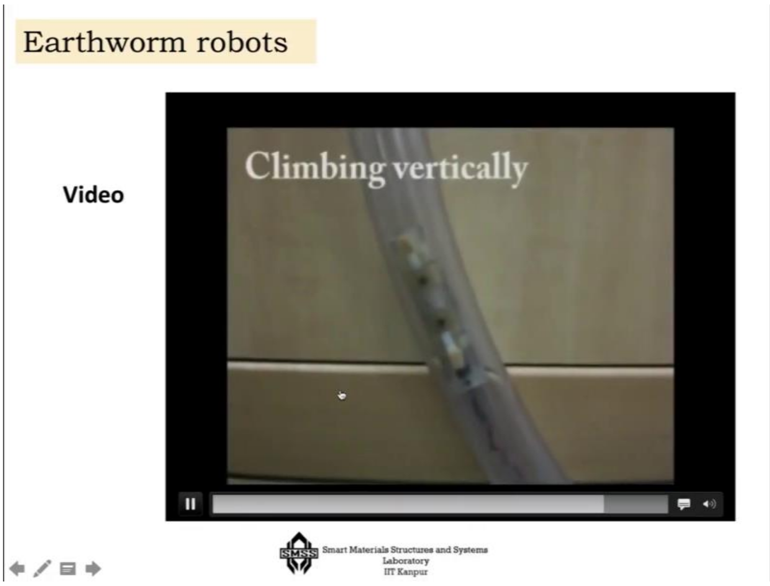

So, you know you can have a versatile movement that you can generate out of this system. So, this is you know, magnetostrictive material. I told you that we would be discussing two materials today; one is the magnetostrictive material, and for which I have shown you that their most generous application for our purpose will be in terms of generating locomotions and that you can do for different, very complex environments you can do it. Of course, you can use such materials for sensors as well; but mostly, it is used as actuators.

Now, other than these two, there is also a third way of creating motions, which we will discuss today, and that is with the use of certain artificial muscles. Now, one of the artificial muscle categories is actually metallic alloys, and it is known as popularly shape memory alloys. So, let us have a look into how these shape memory alloys behave, how we can actually use them in terms of actuations, and in some cases, as sensors as well.

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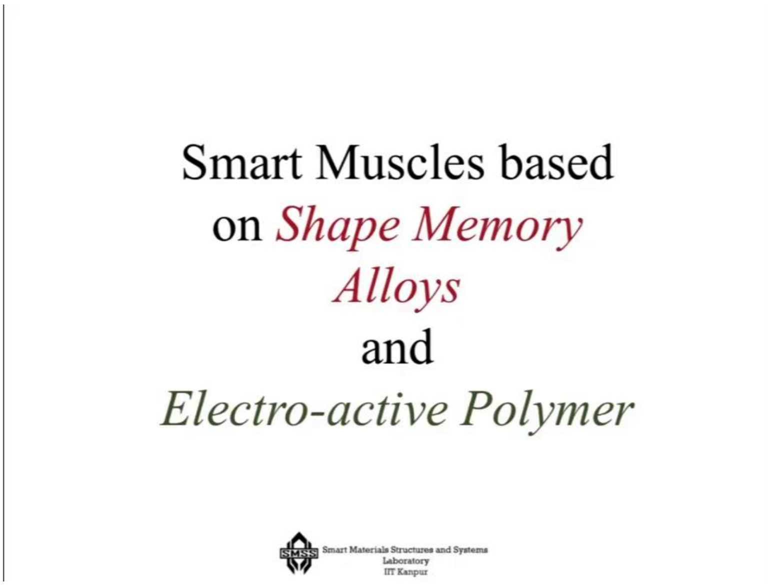

Let us look into the shape memory material. So, we look into these smart materials based on shape memory alloys and electroactive polymer, and today, we will specifically focus on shape memory alloys.

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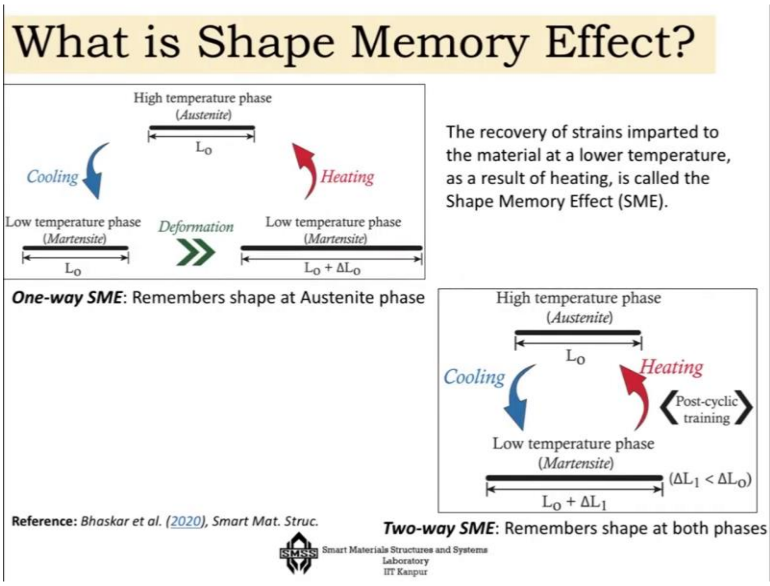

Now, what is a shape memory effect? It is some memory right, and it is a memory, as the name suggests, is related to shape. So, precisely, this material has a memory in its parent's stage, which is called the austenite stage, which happens at a high-temperature phase.

So, generally, what we do is that we cool this material. So, it comes to a low-temperature phase on a martensite phase, then you carry out all the deformations, and then, whenever you are heating it, it will go back to its memorized shape at the austenite phase.

So, that memory is called a shape memory effect. Now, in some cases, it can memorize both the austenite and martensite stage, if you properly train it. So, this case is called a one-way shape memory effect, whereas if one can adequately train it so that both the phases, it can memorize its shape. It is called a two-way shape memory effect.

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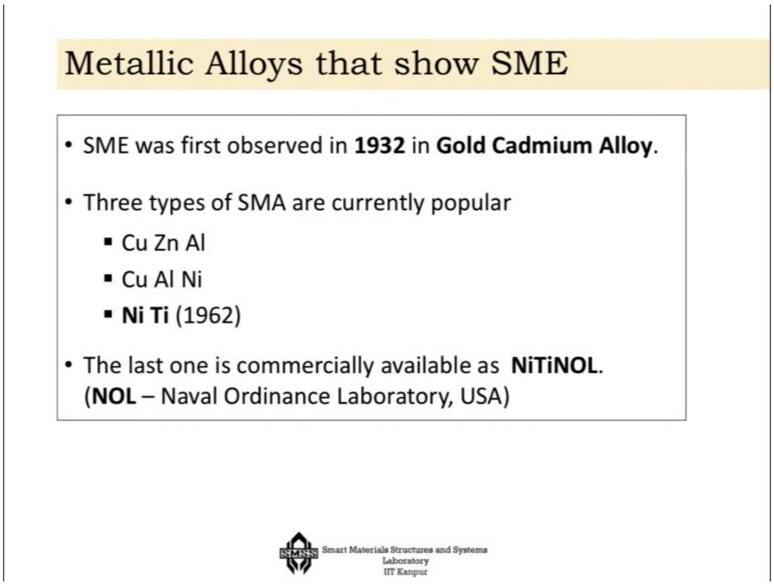

So, you can develop both the type of such shape memory effects. Now, the materials which show such shape memory effect it was first observed that in 1932 in Gold Cadmium Alloy.

Later on, it was found that there are other alloys like ternary alloys of copper, zinc and aluminum or copper, aluminum and nickel, or the best one is called nickel-titanium. In fact, again, Naval Ordinance Laboratory discovered it. So, their name goes with the whole thing, and it is popularly known as NiTiNOL today. So, it is a particular ratio of about 45 to 55 percent of nickel and titanium, which actually makes this NiTiNOL material, and it shows a substantial shape memory effect.

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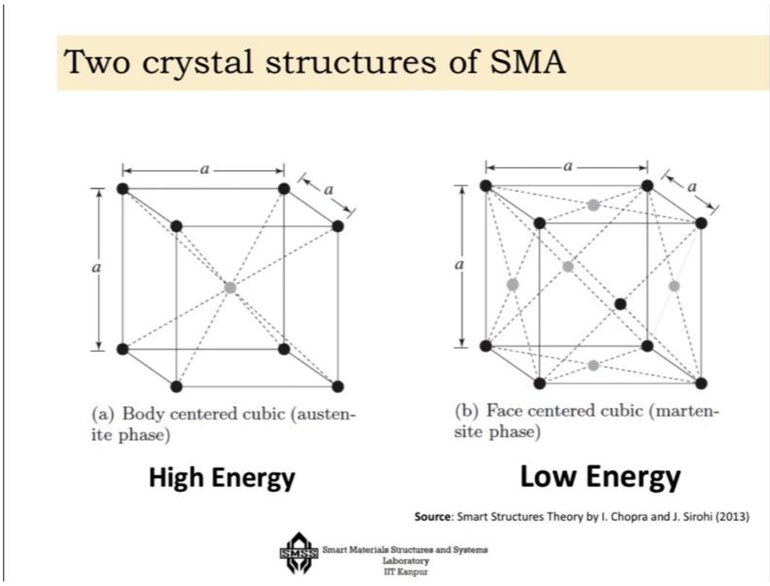

Now, as I told you that the shape memory material actually has two different types of structures. In the austenite phase, it has a body-centered cubic structure. You can see the atoms at the corners and at the center of the body; whereas at the low-temperature phase, it has a face-centered cubic structure, you can see that instead of just at the center of the body, there are these atoms which nicely comes into the center of the faces.

Now, something, if it is inside the center of the body actually inherently, makes it harder and if it is an FCC, it inherently the face-centered cube is actually a more flexible structure. The other thing to note is that at the BCC in the austenite phase, these crystal structures of SMA is nearly cubic in nature.

So, all the lattices are equally dimensioned, whereas, in this case, so in the martensite phase, it becomes a tetragonal structure. So, where you can see that the sizes are not the same, you know it would be different essentially.

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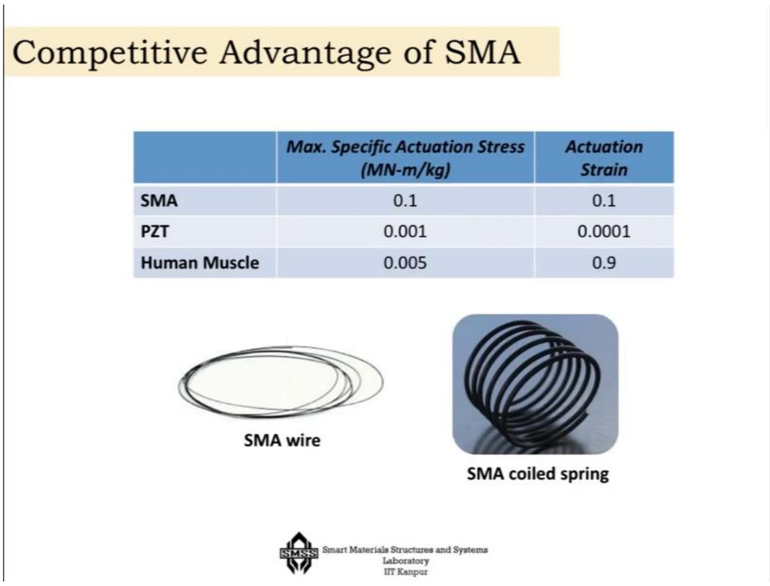

	Max. Specific Actuation Stress (MN-m/kg)	Actuation Strain
SMA	0.1	0.1
PZT	0.001	0.0001
Human Muscle	0.005	0.9

Essentially, these directions it would be different in comparison to the other two directions. So, this is what is the crystal structure of SMA and why we go for an SMA is that you get considerable actuation stress, for example, something like 0.1 mega Newton meter per kg in comparison to PZT, it gets about you can see here that 100 to 1000 times, in fact, more you can get you to know I mean some in between you can get for the SMAs. And also, in comparison to human muscle also you can get a very high amplification, not as high as PZT, but still, it is relatively high.

So, once again, you know you are you know coming after 0.5 here. So, it is slightly less than 100 times that you are getting through this; the strain is also very high. So, essentially you are getting immense stress and strain out of the system, and that is what is very lucrative, and you can get these materials both in wire form as well as in a springform. Spring forms give better stress and deformation, but the only catch is that the spring form is actually more complex to analyze.

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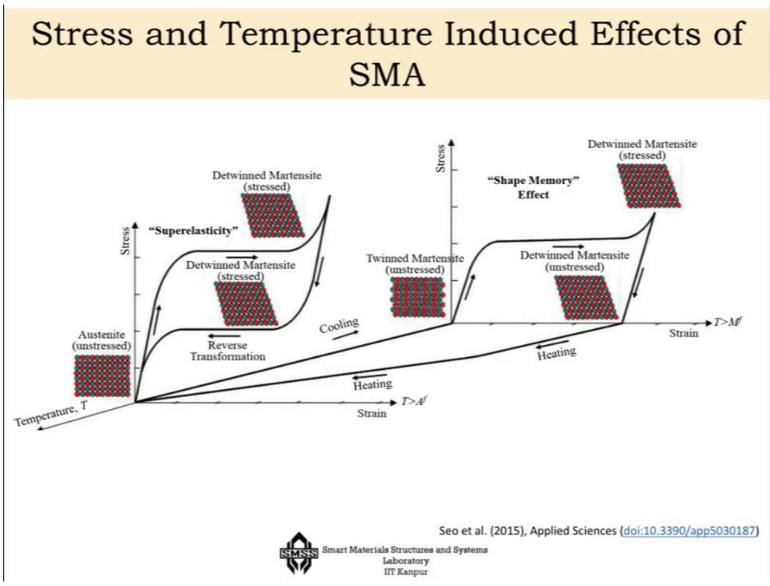

So, modeling is a little bit difficult in the springform. Now, if you look at this diagram very carefully, it actually describes the entire process. As you can see here that in these cases, you know we have the stress, three-axis strain, and temperature. So, let us say the material is first starting from this level when everything is 0.

Now, if I apply the stress and to begin with, let us say that it is at the austenite phase. If I apply the stress, it will deform until beyond a point, it will behave almost like a plastic deformation and then, if I reduce the stress, this plastic deformation will get you to know reversed.

So, this can happen inside the austenite phase; but if you cool this material, let us say you are in the martensite phase, then if I increase the stress, it will then go to the plastic deformation, it will go to detwinned martensite. I will once again reduce the stress, now it will not go back to 0 strain, it will be somewhere here and then, if you heat it up, only then it will come back to its parent phase.

So, that is what is the shape memory effect and also, the hysteresis in this effect the stress-based effect is also called superelasticity. So, these are the two effects that are generally observed in the shape memory alloy.

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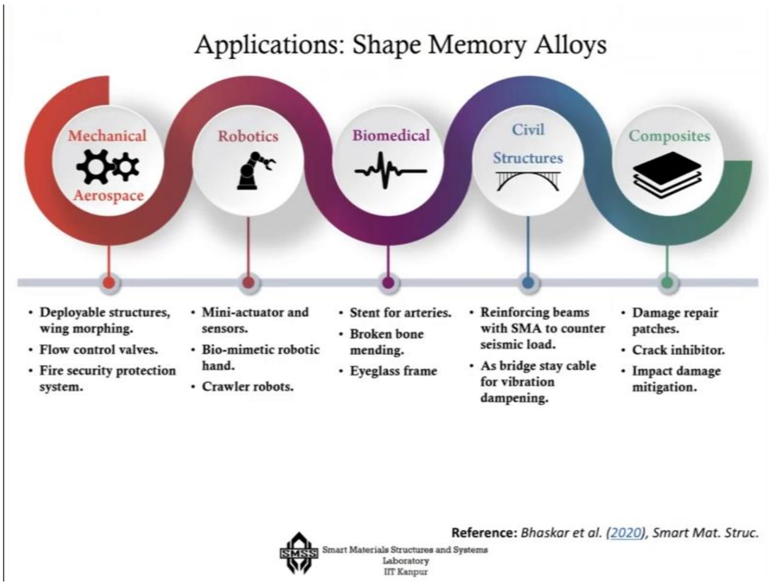

Applications, as I told you, is phenomenal; it is increasing every day; mechanical, robotics, biomedical, civil structures, and composite. Specifically, for robotics, it is used in mini actuators sensors, biomimetic robotic hands, and crawler robots. So, there are very many applications of the shape memory alloy today.

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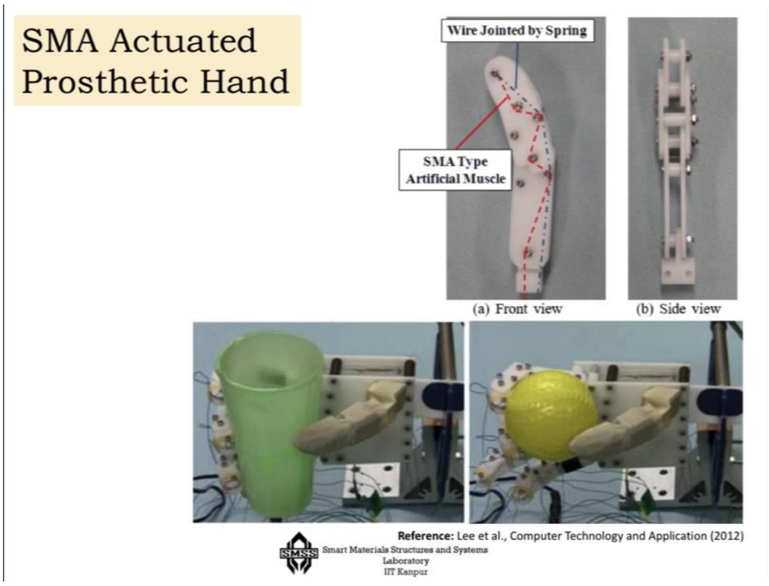

Now, here there are some examples as I am showing you about the SMA type of artificial muscles which is joined using the springs, you can see it in the two views. Now, this can be used for developing the fingers.

So, there were ASIMO fingers which are controlled by Servo Motor can be, in fact, better controlled with less power with the help of SMAs, if you can model it properly and you can actually determine the forces there so that it does not get crushed.

So, depending on the type of element you are holding you can control the force. So, that is the beauty of the SMA actuated prosthetic hand. SMA is also used in terms of sensors. So, there are not many applications, but we have devised some applications for SMA as sensors as well.

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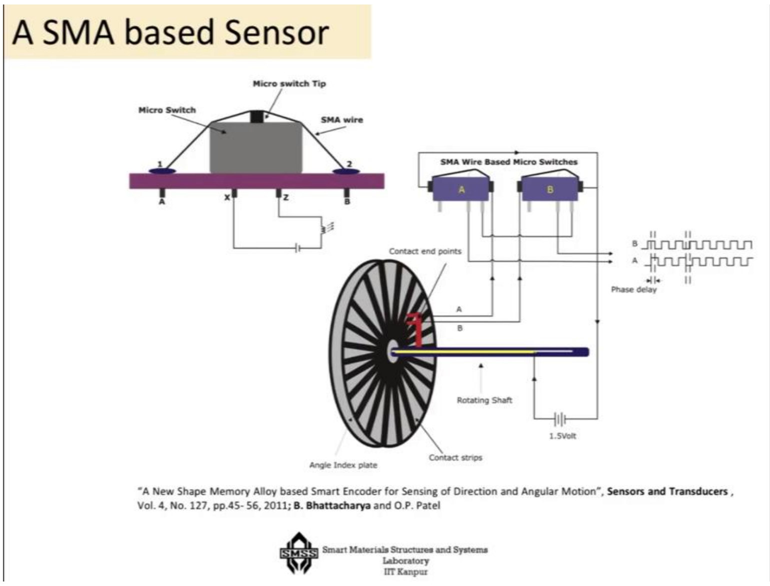

You can see here is an SMA based sensor, where there is a rotating drum which is having the contact endpoints, and these two points are connected with the help of styluses and SMA wires operate these styluses.

Now, the moment the two styluses are on conductive tape, there is a current that will pass through, and as soon as there is a current that will pass through those, there were heating effects and the switches A and B will operate. So, that you will get a signal out of them, and once one of the stylus you will miss during the rotation, it will not be able to operate, and hence, you will see that the signal will come down to 0.

So, by measuring these two counter outputs, you will be able to find out how much of rotation is happening on this particular drum. Thus, you can actually make a superior sensor a very robust sensor out of it. The details of it are again available in one of our papers in sensors and transducers.

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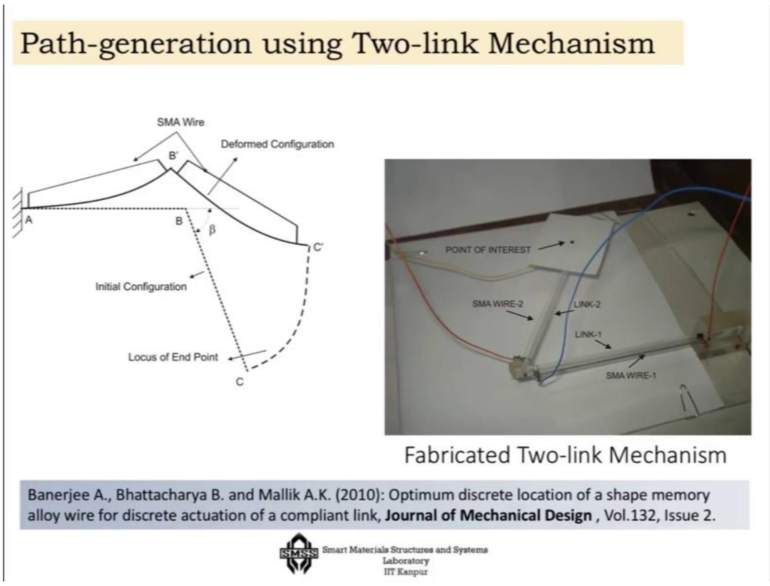

Now you can also use these SMAs in terms of muscles; let us say if there are two compliant links. So, there are two links, and I have attached them with two SMA wires, and you can see that by doing that, you can very nicely manipulate the tip of this whole system.

So, this is a fabricated two-link mechanism, where SMA wire is controlling essentially two SMA wires, are controlling the two link deformation and by that, it is controlling these point of interest, the topology of this point so that it can be used in terms of various types of manipulations. For example, now, this is once again is reported in one of our papers in the Journal of mechanical design.

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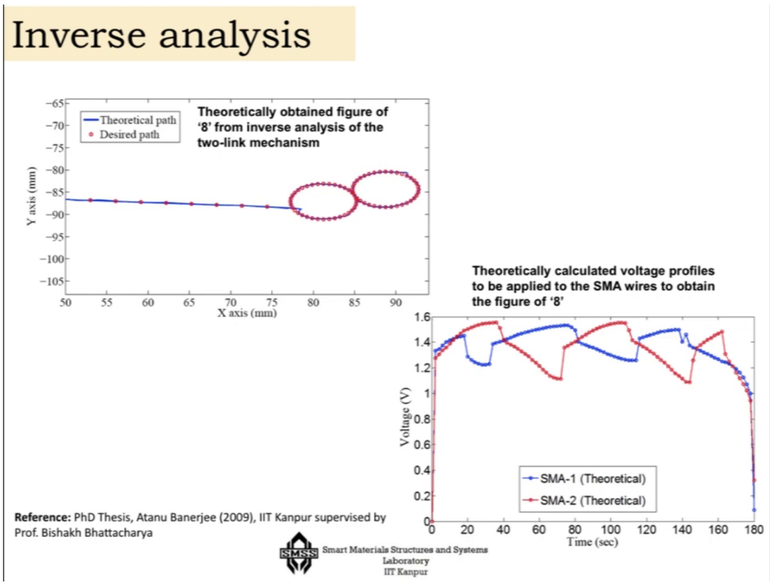

Now, you can generate many different types of shapes. So, here, for example, you can see that there is a figure of 8 that is generated by using the shape memory alloy-based two-link mechanism.

In fact, one can actually find out that what kind of current through simulation will be able to generate it, and you can feed that same current a loop into the system like this type of a system, you feedback the currents in the two SMA wires related to the two links; link one and link two and you will be able to get the desired deflection in the system. So, this is you know this is one way of using SMA for developing nice manipulators, which can be used for finger movements things like that.

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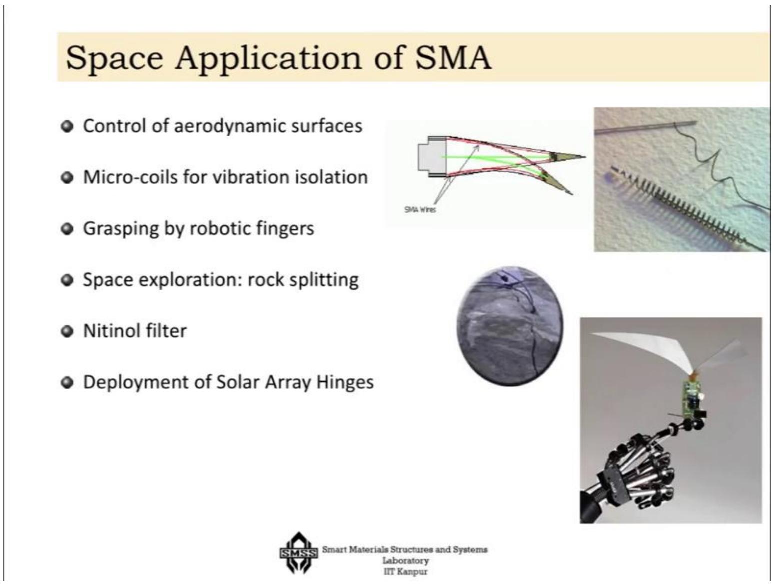

Now, it is used in general for control of aerodynamic surfaces like for control of motion, for vibration isolation, for grasping of robotic fingers, space exploration, and for the deployment of solar array hinges. Indeed many applications, it is increasing day by day.

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Properties of a few Smart Materials

Properties	PZT	PVDF	Terfenol-D	NiTiNOL
Free strain(ppm)	1000	700	2000	20000
Elastic Modulus (GPa)	62	2.1	48	27-Martensite 89 - Austenite
Band	0.1Hz - 1 GHz	0.1Hz - 1GHz	0.1Hz - 1 MHz	0 - 10 Hz

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What is the advantage? I am just giving here a quick comparison PZT, which was a piezoelectric material. Its strain level is 1000. PVDF, which is the plastic piezoelectric material, let us call it; its strain level is 700. Terfenol – D has a strain level of 2000, which means it gives more strength than these two.

NiTiNOL will give you about 20000; it gives much more than all the three. The only thing is that in terms of elastic modulus, this one is a little bit softer; whereas this one Terfenol - D and PZT both of them are equally high and then, from the bandwidth point of view, Terfenol - D is the SMA is the smallest, then Terfenol - D and followed by the piezoelectric material.

So, this is just the conglomeration of the properties so that we can make a quick decision in terms of the use of the smart material. Now, this is where we will put an end to this lecture. In the next lecture, we will look into another kind of a smart muscle which is made of shape memory or which is made of electroactive polymers, shape memory alloy we have discussed today.

Thank you.