Foundations of Cognitive Robotics
Prof. Bishakh Bhattacharya
Department of Mechanical Engineering
Indian Institute of Technology, Kanpur

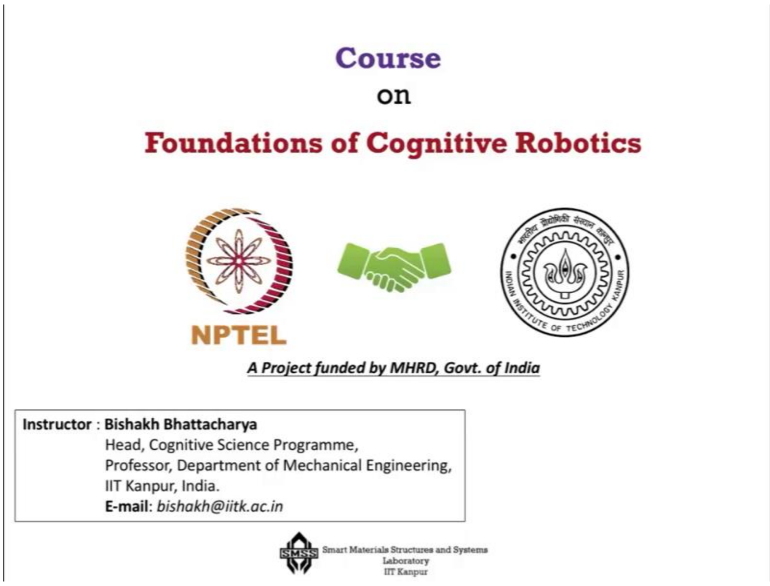
Lecture – 02

Welcome to the 2nd lecture on Foundations of Cognitive Robotics. In the last class, I talked about a basic introduction of cognitive robotics, where I told you that what is the source or inspiration of these term cognitive. And how cognitive robotics is different is unique from other branches of robotics. I also told you if you remember that what are the different types or characteristics of interactions that are possible in a robotic system in order to develop an intelligent robotic system.

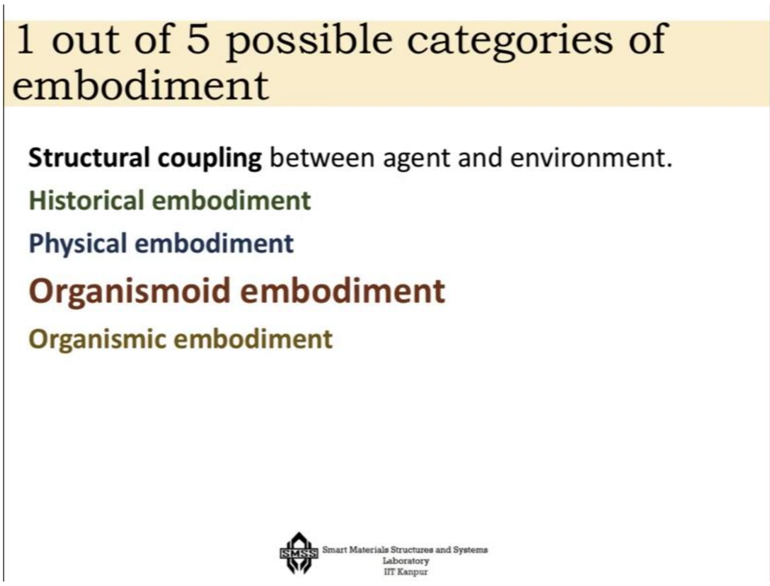
And we have made these graduations from strong to weak artificial intelligence strong to weak AI. Like for a robust AI system, I told you that embodiment is not a precondition you can have simple coupling; you can have historical coupling with the environment, and that will be good enough for a strong ai system. Whereas, for a weak AI system where we are talking about things like cognitive robotics, the physical embodiment is very much required.

Now, there are two subcategories under a physical embodiment, which are organismic embodiment and organismoid in embodiment. And I will talk about these different types of embodiments in this particular lecture. Also, I will tell you that how we can develop such cognitive robots using a certain special class of materials called smart materials. And thus, we will be able to build up organismic robots, and there will be a hope of developing cognitive robots through that.

(Refer Slide Time: 02:37)



(Refer Slide Time: 02:40)



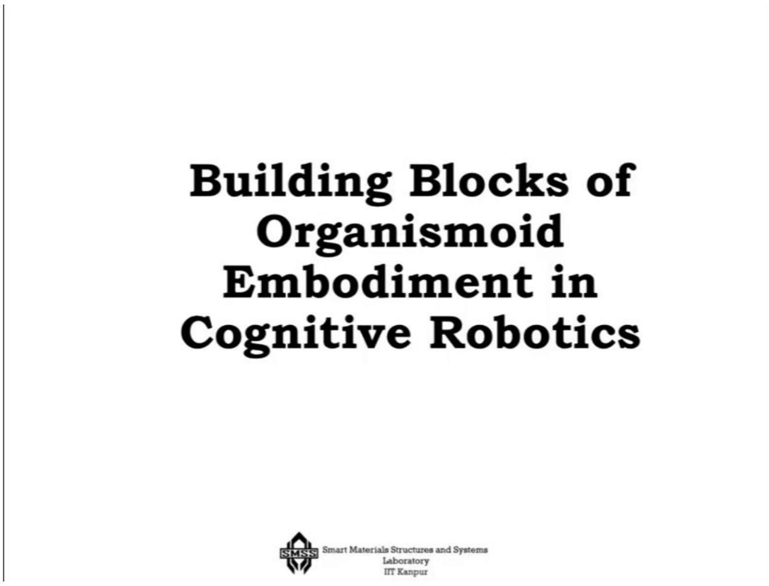
So, in this second lecture on the foundations of cognitive robotics, we will focus on organismoid embodiment. So, all other couplings in a structural coupling or historical embodiment and the very futuristic embodiment, which is organismic embodiment these are the things which will not focus at this moment. Organismoid embodiment, which is the basic requirement for cognitive robotics, will be in focus first.

Now, when we talk about organismoid embodiment, what is it that comes into your mind first? Remember, in our last lecture; I have shown you a small video from Honda on the performance demonstration of a robot, which is a humanoid robot; that is the ASIMO robot.

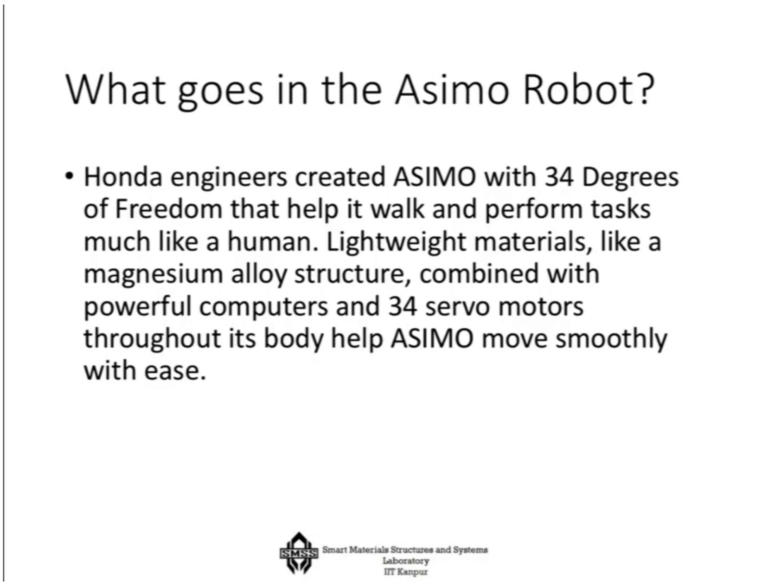
Now this particular robot, how do you classify it would you classify it to be an organismoid robot. And if you classify this to be an organismoid. So, how much human-like is this particular robot?

So, let us look into Honda specifications and let us see how much humans like is this ASIMO robot.

(Refer Slide Time: 04:25)



(Refer Slide Time: 04:29)



So, we will talk about the building blocks, and in this direction, let us look into what goes into the ASIMO robot. Now Honda engineers have created ASIMO with 34 degrees of freedom. This 34 degrees of freedom essentially means that there are 34 independent ways in which the ASIMO robot can move it is different limbs or body parts. And that actually helps it to walk and perform many tasks much like a human, exactly not like a human, but much like a human. You have seen in the last class in the last video that I have shown that how it was delivering a glass of dreams to the lady.

Now, this ASIMO, apart from the fact that it is made of 34 degrees of freedom structurally it is made of a lightweight material, which is a magnesium alloy structure, and it is combined with powerful computers.

And it is these two combinations; that means, by choice of lightweight material and by choice of these 34 degrees of freedom, we are able to see the performances of the ASIMO robot. Well, you will be interested to know that in comparison to the ASIMO robot, what the degrees of freedom to a real human are. And then, only we will be able to judge the performance of the ASIMO robot.

(Refer Slide Time: 06:11)

How many DOFs are there in human?

HEAD	Neck joint (Up/Down, Left/Right Rotation)	3 DOF	
ARMS	Shoulder joints (Forward/Backward, Up/Down Rotation)	3 DOF	
	Elbow joints (Forward/Backward)	1 DOF	
	Wrist joints (Up/Down, Left/Right, Rotation)	14 DOF =	7 DOF x 2 arms
HANDS	4 fingers (to grasp objects) / Thumb	26 DOF =	13 DOF x 2 hands
HIP	Rotation	2 DOF	
LEGS	Crotch joint (Forward/Backward, Left/Right Rotation)	3 DOF	
	Knee joints (Forward/Backward)	1 DOF	
	Ankle joints (Forward/Backward, Left/Right Rotation)	12 DOF =	6 DOF x 2 legs
TOTAL		**57 DOF**	

Smart Materials Structures and Systems Laboratory
IIT Kanpur

If you find out how many degrees of freedom are there in human. You will see that, for example, our head in the neck joint can have 3 independent movements; up or down, left or right, and rotation, so it has 3 degrees of freedom.

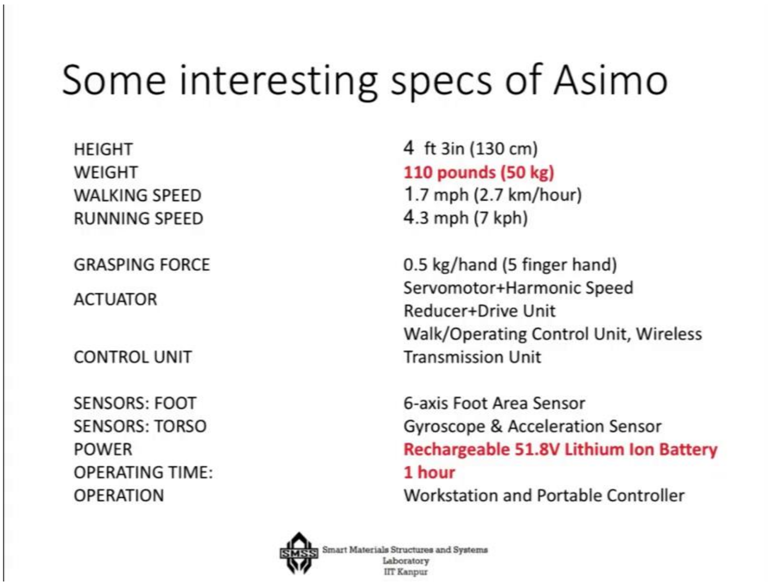
Similarly, in the shoulder, it has 3 degrees of freedom again. The elbow joints have 1 degree of freedom, the wrist joints, in comparison, have much higher degrees of freedom 7 degrees of freedom in each one of the wrist, so for the two wrists that we will make it 14 degrees of freedom.

The maximum number of degrees of freedom is there on the fingers. That is why our fingers know the in comparison to ASIMO’s; ASIMO looked like so much like a robot. Because if you look at our fingers, we will be having 13 degrees of freedom in each hand, so that means a total of 26 degrees of freedom.

Then the hip is having 2 degrees of freedom, the crotch joint in the leg is having 3 degrees of freedom, the knee joint 1 degree of freedom, and the ankle joint will be having 6 degree of freedom each, which means; two ankle joints will give you 12 degrees of freedom. So, in all, it is about 57 degrees of freedom.

So, compare our 57 degrees of freedom to the ASIMO robots 34 degrees of freedom, and you to be able to know that how much steel we have to achieve in the robotics. There is also some more thing to compare; how about the weight of the ASIMO robot with these 34 degrees of freedom and how much of power it requires. Let us go back to the specifications of the Honda robot and let us check that.

(Refer Slide Time: 08:16)



If you look at some interesting specifications of ASIMO, which I gathered from the Hondas website; it’s height is about 4 feet 3 inches; it is just like the height of a child. Weight is 50 kg well, that is, little high in comparison to a child, walking speed and running speed are slightly on the higher side as we can see 2.7 kilometers per hour.

Walking speed and running speed is about 7 kilometers per hour, gasping force a little bit in the lower side, about 0.5 kg or 500 gram per hand. I am sure that a kid can lift slightly more weight than 500 grams. Actuator wise this 34 degrees of freedom comes in the expense of 34 servo motors.

In fact, that is what gives the maximum cost to this robot. And the control unit is having the walking and operating control unit wireless transmission units. It has sensors, for example, in the foot, it has torso level sensors in terms of gyroscopes and acceleration sensors.

And again, the negative side is the power it needs a 51.8 volt lithium-ion battery; it is very substantial. Also, lithium-ion battery is quite dangerous due to its weight. And the operating time that we get that is also very low if you look at it is just 1 hour. So, what we can figure out from this specification is that there are at least three points in which ASIMO is still far away from a good organismoid robot. One is in terms of course, the degrees of freedom it has 34 degrees of freedom whereas you know in nature the human that it mimics that has 57 degrees of freedom.

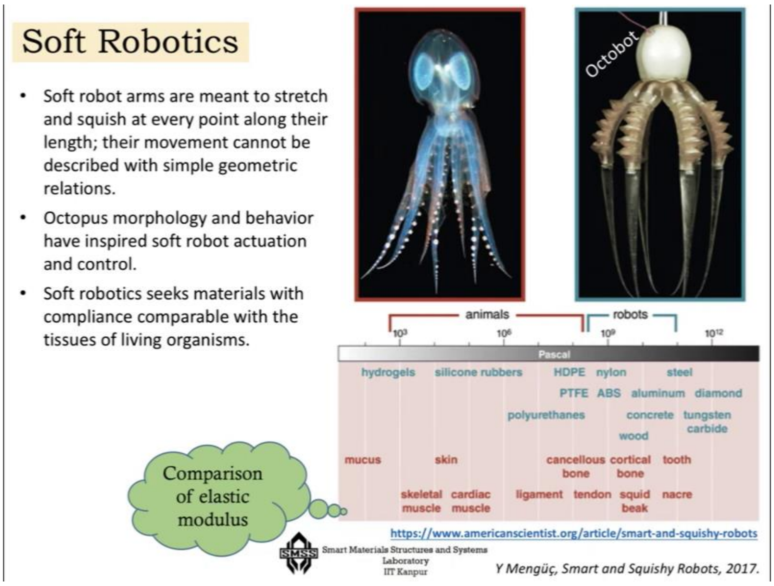
And it has a substantially high weight of more than 50 kg despite using a very advanced class of materials also, it needs a very high power, and it can work only up to an hour or so. So, these are some of the limitations of the best current available robot, which is close to an organismoid robot.

So, all these things, what does it point to? It tells us that we need to improve in terms of the overall weight or the bulkiness of the robot and also in terms of the overall power consumption of the robot. So, what is the solution in front of us?

(Refer Slide Time: 11:37)

If we look into the new developments of muscles in this new age, we will see that there is a new branch of robotics first expanding, which is also known as soft robotics.

(Refer Slide Time: 11:44)



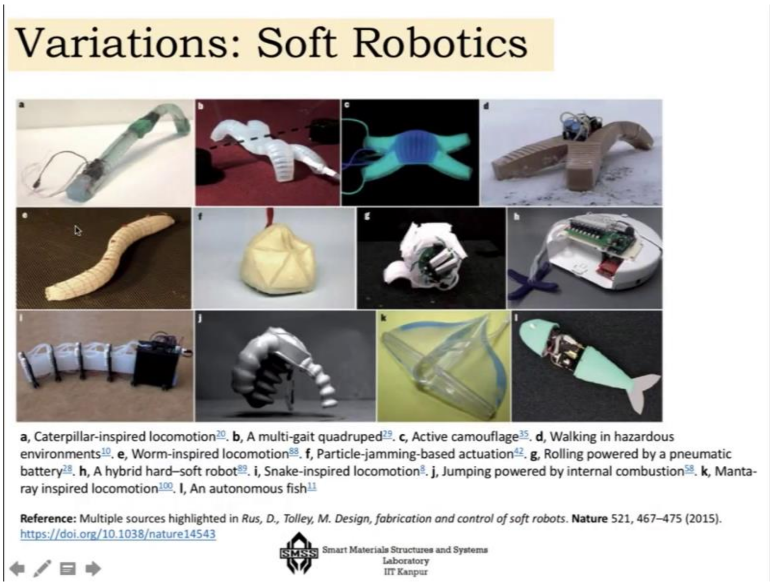
Now, under soft robotics, the robotic arms are meant to stretch and squeeze at every point along their length. Furthermore, their movement cannot be described with simple geometric relations because it is too complicated it is a large deformation motion much unlike the way we are used to doing it; let us say for a rigid robot system with the help of kinematic chains. It is very difficult to describe this kind of a flexible robotic link with this type of robotic system.

So, here you can see an octobot or a octopus morphology you know kind of thing which is mimicked in an octobot system. Now one of the thing if we compare between the robots and the animals, we would see that; robots traditional designs of steels is far stronger than any natural naturally living material. Let us say the nearest will be the teeth or the nacre and if you go for softer materials like wood or ABS plastic, then possibly it will be closer to the cortical bones or a squid beak.

If you make your robot even softer like; high-density polyethylene or polytetrafluoroethylene or polyurethane, then we will come closer to cancellous bones, ligaments, tendons, etcetera. If you can make your robot further soft like silicone rubbers, then you will get some of the muscles like cardiac muscles, and even in a softer range almost close to hydrogels, you will start to get the skeletal muscles.

So, thus this you know comparison is aptly telling us that the direction to which we have to take our soft robotics, but Is weight is the only concept? No, we have to also keep in mind that we have a constraint of the power; so many servo motors, which makes it very expensive to afford.

(Refer Slide Time: 14:21)



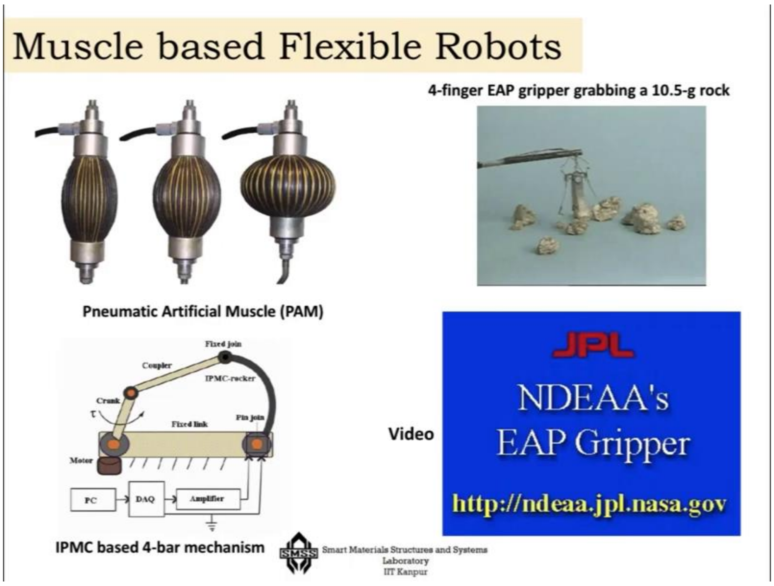
Now you look at the different variations of soft robots like; this one is a caterpillar inspired locomotion and then a multi gait quadruped robot again based on soft material. And active camouflage one you can actually play with metamaterials and optically coupled properties to develop active camouflage.

Walking in hazardous environments type of robots and then worm inspired locomotion in robots and then particle jamming based actuation rolling powered by a pneumatic battery and hybrid hard and soft robot kind of combinations.

And then we have this snake inspired locomotion, jumping powered by internal combustion. Then there is a manta ray inspired locomotion and an autonomous fish. All these are various types of soft robots that are coming up very fast and with the intention of how we can reduce the weight of the robot.

But also as I told you that functionally you need to improve or replace these classical servo motors; in order to make it more sustainable, feasible and low power consuming.

(Refer Slide Time: 15:49)

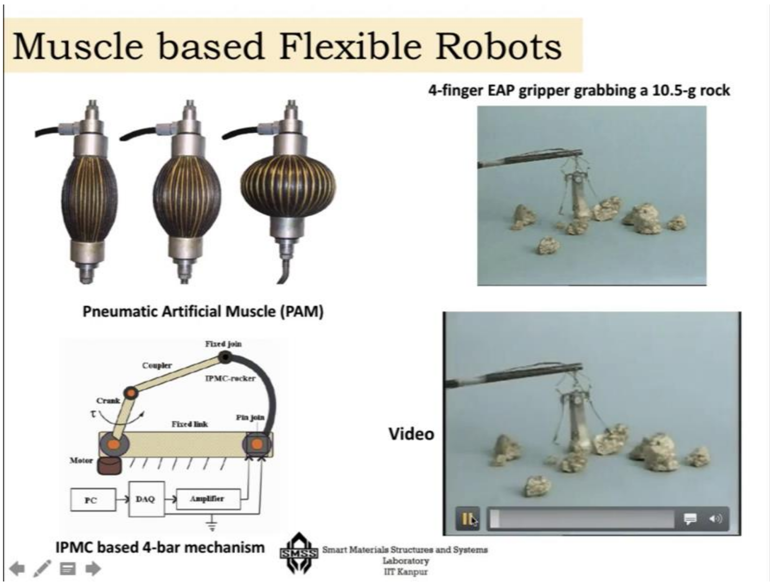


So, we need to think about the development of muscle-based flexible robots. The first stage towards that is the development of pneumatic artificial muscles or PAM's. Moreover, this PAM's were the first step where the air pressure is used in terms of compressing and getting a muscle like motion from the system.

Now, however, the compression itself is quite heavyweight. So, we need to change from a compressor-based system to let us say a solid-state kind of actuator system. And one of the very interesting candidates towards this is ionic polymer matrix composites or IPMC'S.

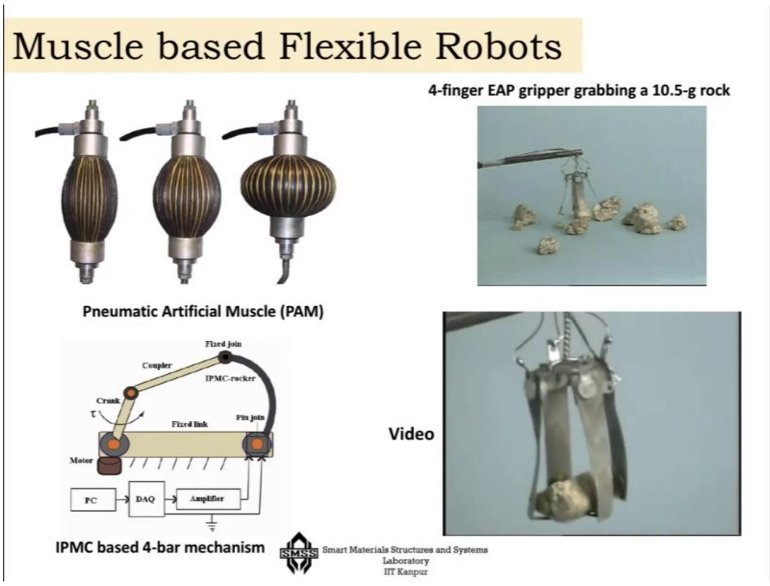
These are a general class of electroactive polymers like here you can see; a four-finger electroactive polymery gripper which can grip up to the extent of 10.5 gram of rock and this is used by NASA in an EAP Gripper for you know extra outside the earth in one of the planets planetary missions to collect the debris; I can show you that how this EAP would work.

(Refer Slide Time: 17:09)



You can see that such a large deformation you are getting from the electroactive polymers. And then how each one of the four fingers has to work together with the last deformation, and then they have to grab the object.

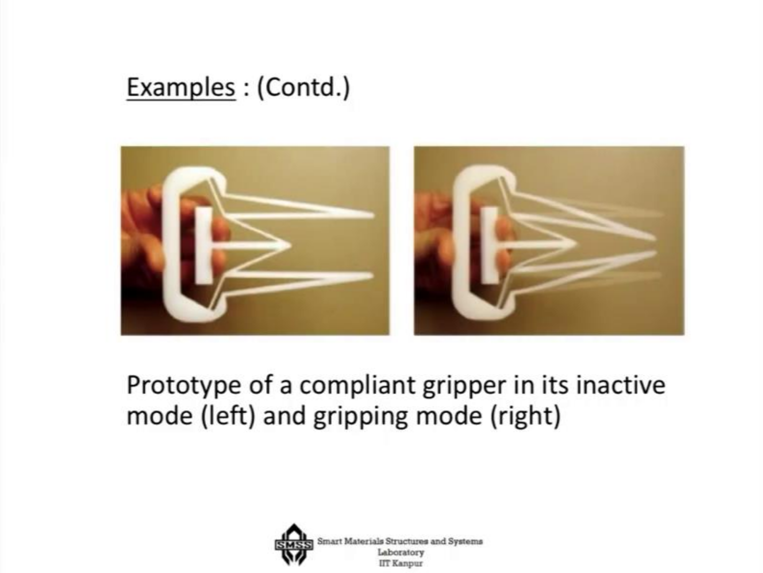
(Refer Slide Time: 17:17)



Which is white, you can see that it has to it has deformed a lot. So, that is something without the use of any motor is challenging just by deforming it to the help of the direct transformation of electrical energy to mechanical energy and when placing it at a different location.

You can do much more complicated works with the help of this kind of IPMC rocker. Today we have an even more impressive group of materials that can perform amazing fits, and they can be easily embedded and integrated in order to form actuators that would go very well with soft robotics. And can make our dream of developing cognitive robots this are the groups of materials which are known as smart materials.

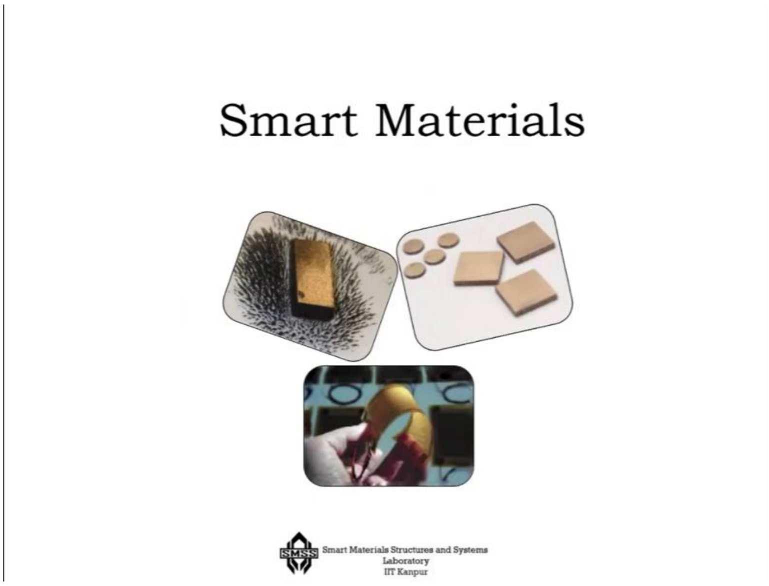
(Refer Slide Time: 18:18)



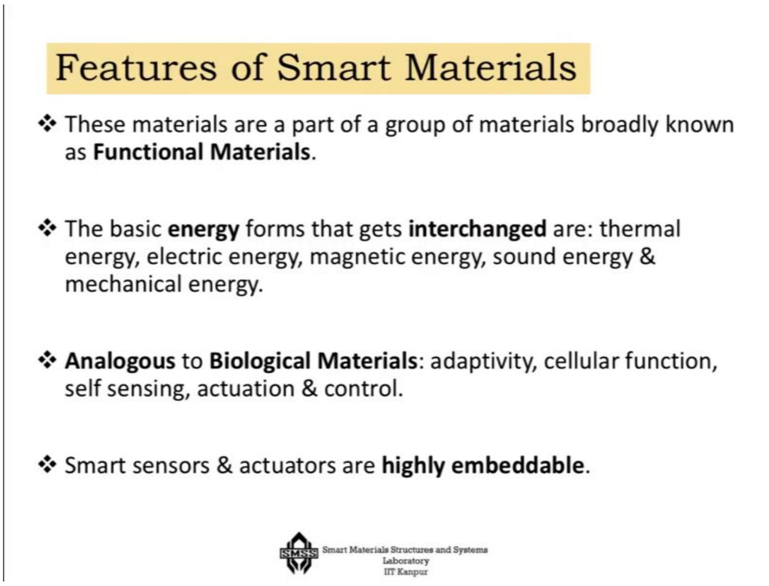
Now, before we talk about such smart materials, we have to keep in mind that the mechanisms also have to be made compliant. For example, here you can see that this is a gripper and the gripper ends you can see a large deformation you can make with the help of these closing down between the two.

Now what here has been done using the fingers can also be done with the help of smart materials, and then you can get a substantial deformation. So, even though the smart materials can be used at the back end in order to get a large amplified motion, you need to make such contraptions of compliant mechanisms for grippers.

(Refer Slide Time: 19:06)



(Refer Slide Time: 19:17)

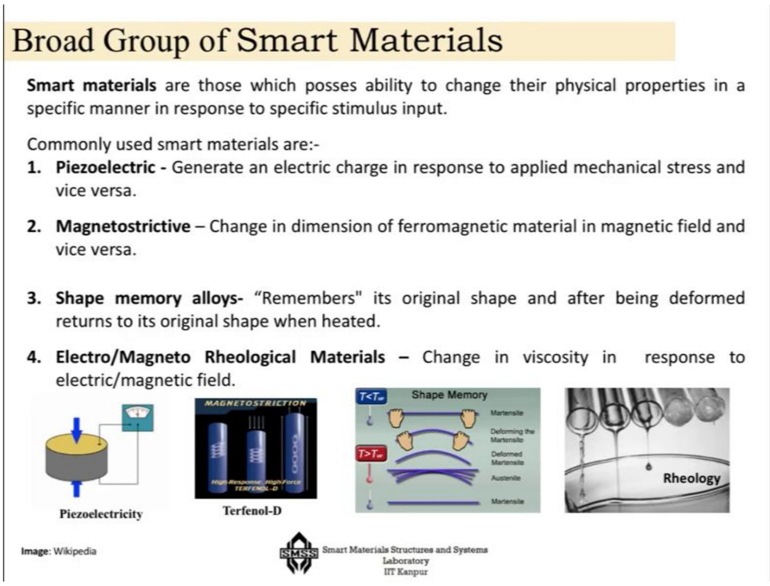


Now, let us talk about smart materials. In this group of materials, the features of such materials are that; they are functional in nature, and the basic energy forms that get interchanged in such materials are between thermal energy to mechanical energy, between electrical energy to mechanical energy, magnetic energy to mechanical energy, or sound energy to mechanical energy.

As I told you earlier also that energy can only be transformed. So, in this case, we have to manipulate between these transformations in order to get our intended type of actuation or type of sense. Now this material's behavior, which is why they are so much important for soft robotics, is that they are analogous to biological materials.

Like there the nature of adaptivity, cellular function, self-sensing, actuation, and control. And moreover, these sensors and actuators are highly embeddable. So, as different energy forms are interchanged in smart material. Let us look into these different types of smart materials from an input-output classification point of view.

(Refer Slide Time: 20:36)

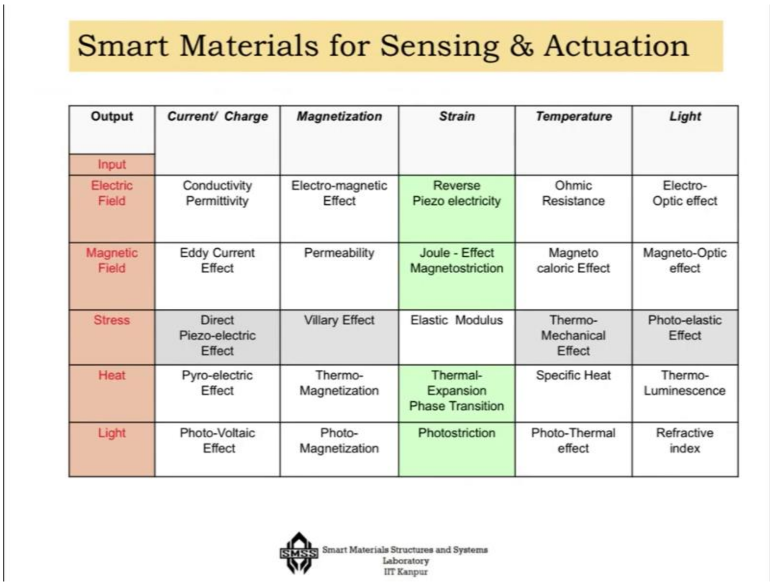


There is a broad group of smart materials like; piezoelectric. In this case, the input is electrical energy and the output is mechanical deformation mechanical energy. And then we have magnetostrictive materials where the input is for the use of for the group of ferromagnetic materials; the input is magnetic energy.

And the output is once again mechanical energy in the form of mechanical stress and deformation. And then for shape memory alloys, it remembers it is original shape after being deformed and it can go back to the original shape.

So, this is by actually exploiting the change from thermal energy to mechanical energy. And we also have some special groups of rheological materials which are like electro magneto rheological materials where; it is the viscosity that changes in the material. So, thus there are these different types of materials and if we look at these from an input output point of view.

(Refer Slide Time: 21:41)



Smart Materials for Sensing & Actuation

Output / Input	Current/ Charge	Magnetization	Strain	Temperature	Light
Electric Field	Conductivity Permittivity	Electro-magnetic Effect	Reverse Piezo electricity	Ohmic Resistance	Electro-Optic effect
Magnetic Field	Eddy Current Effect	Permeability	Joule - Effect Magnetostriction	Magneto caloric Effect	Magneto-Optic effect
Stress	Direct Piezo-electric Effect	Villary Effect	Elastic Modulus	Thermo-Mechanical Effect	Photo-elastic Effect
Heat	Pyro-electric Effect	Thermo-Magnetization	Thermal-Expansion Phase Transition	Specific Heat	Thermo-Luminescence
Light	Photo-Voltaic Effect	Photo-Magnetization	Photostriction	Photo-Thermal effect	Refractive index

Smart Materials Structures and Systems Laboratory IIT Kanpur

The inputs can be categorized in terms of the electric field, magnetic fields, stress, heat or light for that matter even light can be used as input. And outputs can be in terms of charge, magnetization, strain, temperature, and light. Now, if you look at these, let us say like in a matrix form, then the diagonal terms are something which are the material properties which is very common in the material.

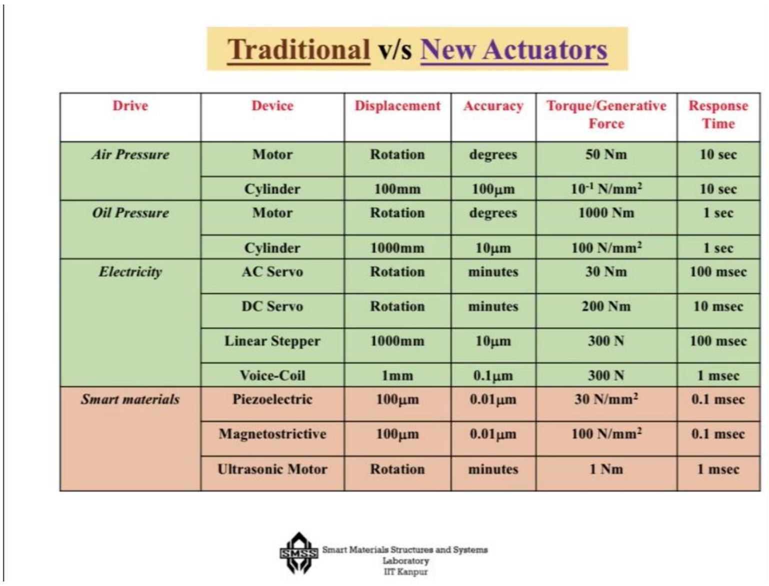
So, they are not very smart properties, but it is the off-diagonal terms. Particularly this green row column and this gray row, which is of very useful nature to us. For example, the electric field as an input and as an output it is creating strain is what is known as reverse piezoelectricity that is what is used in piezoelectric materials or even in the IPMC example that I am showing you a few minutes before. And this is one such kind of an off-diagonal property of a smart material.

Similarly, if you can achieve the deformations using magnetic energy, then it is called Joule effect magnetostriction so this is also another off-diagonal term. For a heat for the shape memory alloys, it is thermal you know thermal-induced phase transition, and for a light, it is photostriction. Now, this green column this is corresponding to the actuator development.

Many of these materials can also be used as sensors, and here this gray row is significant. Like if you use, for example, stress as the input mechanical stress and by exploiting the direct piezoelectric effect, you can build up a sensor that will give current or charge as an output.

Similarly, using the Villary effect in some materials, you can get magnetic field change magnetization change as an output. Change of stress creating strain is a very familiar thing of elastic modulus; there is no smartness here, but if I change the stress and if the temperature changes, there is a thermomechanical effect that is related to. Similarly, if the electric property changes, there is a photoelastic effect, which is also equally attractive in terms of developing sensors.

(Refer Slide Time: 24:19)



Traditional v/s New Actuators

Drive	Device	Displacement	Accuracy	Torque/Generative Force	Response Time
Air Pressure	Motor	Rotation	degrees	50 Nm	10 sec
	Cylinder	100mm	100μm	10^{-1} N/mm^2	10 sec
Oil Pressure	Motor	Rotation	degrees	1000 Nm	1 sec
	Cylinder	1000mm	10μm	100 N/mm^2	1 sec
Electricity	AC Servo	Rotation	minutes	30 Nm	100 msec
	DC Servo	Rotation	minutes	200 Nm	10 msec
	Linear Stepper	1000mm	10μm	300 N	100 msec
	Voice-Coil	1mm	0.1μm	300 N	1 msec
Smart materials	Piezoelectric	100μm	0.01μm	30 N/mm^2	0.1 msec
	Magnetostrictive	100μm	0.01μm	100 N/mm^2	0.1 msec
	Ultrasonic Motor	Rotation	minutes	1 Nm	1 msec

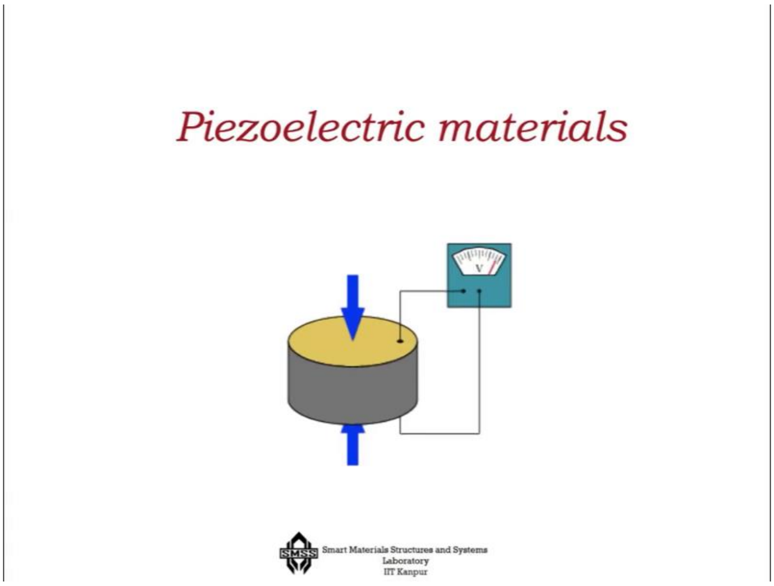
Now, if you compare these materials in terms of actuators and compare them with the traditional actuators like; motors, like pneumatic actuators or hydraulic actuators, we are interested to know that in which way smart materials are better in which way these smart material based actuators will be outstanding in comparison to all the traditional actuators.

If you look at the response times, you can see that all these greens are the traditional actuation system, which is in terms of seconds or milliseconds. And here, for smart materials, you get it in terms of 0.1 milliseconds. So, it is even one-tenth of a millisecond, and that shows why they are swift.

So, their response time is faster, which makes them closer to this kind of organismoid robots. And also, another exciting property their accuracy, they are far accurate then most of these actuators that we are talking about at least 10 to 100 times more accurate these smart materials are. So, in terms of the speed, in terms of accuracy, they are several orders of magnitude better than the traditional actuators.

Now the flip side is that the displacement is lower or the force is also lower, but these two things you can actually compensate by using suitable mechanical amplifiers or by distributing the actuators the smart material based actuators. You know, in terms of just like our muscles, you can distribute it, and you can extract more energy from the system.

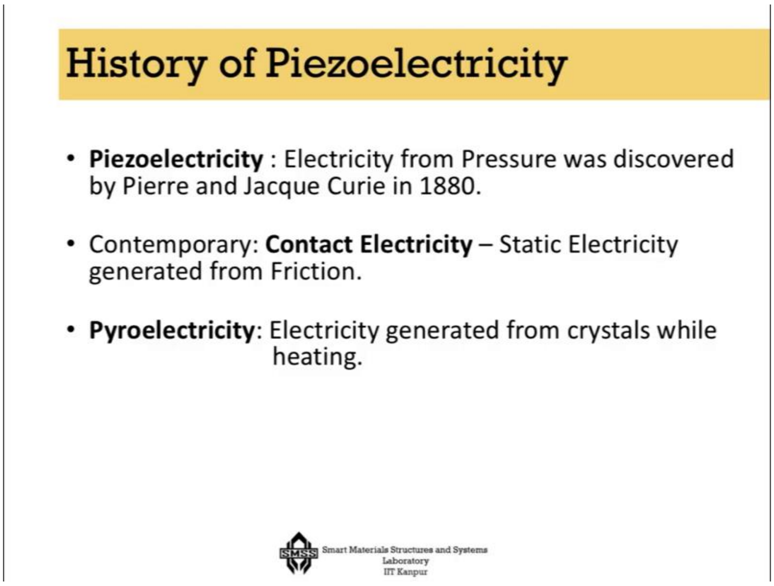
(Refer Slide Time: 26:34)



Now, if you look at the piezoelectric materials because in this talk and today's lecture I am mostly focusing on piezoelectric materials. As you can see here that if I apply force and if I deform the piezoelectric material, you are getting a voltage that is produced in the system.

So, this is what is the direct piezoelectric effect. Where you are applying the force mechanically, and you are getting the voltage out of it.

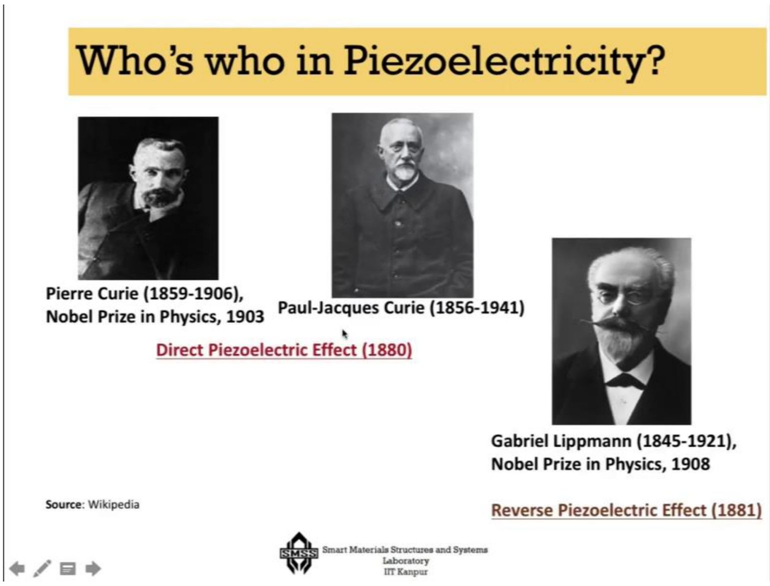
(Refer Slide Time: 27:12)



If we look at these piezoelectric materials close, we will first see that they are not that very new; it was developed around 1880 as you can see that Pierre and Jacque Curie has developed the first found out this piezoelectricity which is electricity from pressure and contemporary electricity.

Where to like; electricity forms static electricity from friction; it was contact electricity or electricity by heating up crystals, which was pyroelectricity. So, when they found out that even pressure in a crystal can generate electricity, this *piezo* means pressure; that is where this new group came into the picture.

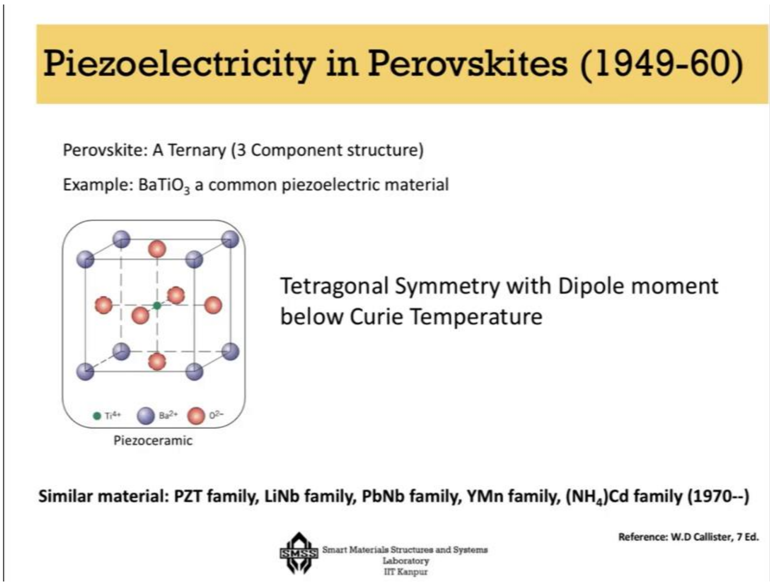
(Refer Slide Time: 27:58)



And as a result of that Pierre Curie and Paul Jacques curie both of them got Nobel Prize in physics in nineteen o three on the direct piezoelectric effect. The direct effect signifies if you apply pressure on the piezoelectric material, you are getting electricity out of it.

Similarly, at a later stage, Gabriel Lippmann theoretically predicted that the reverse is also possible; if you apply electric field, you will get a mechanical deformation for which he got his Nobel Prize in 1908 that is on the reverse piezoelectric effect.

(Refer Slide Time: 28:37)



Now why piezoelectric material is so exotic what is there? So, special in a piezoelectric material that actually gives it this property that as you apply the mechanical force, you are getting an electrical charge out of it.

So, one of the very important groups of piezoelectric material is these perovskites, named after a Russian geologist which was discovered roughly around 1950 or so. And these perovskites are generally ternary structures; that means, it is made of three components like in this example barium titanium and oxygen. So, there are three components that form this piezoelectric crystal.

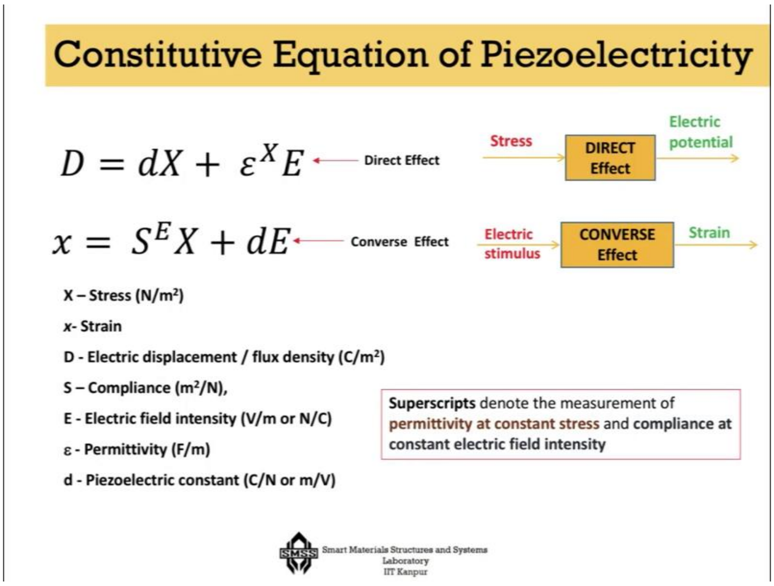
Now, what is so special about this component is that; if you look at the crystal structure of this material, you would see that barium atoms are at the vertices of this tetrahedral these tetragonal structures. And you would see that the oxygen atoms are at the face-centered everywhere, and the titanium, which is the source of this kind of piezoelectricity, is deep inside the geometric center of this tetron.

Now, this titanium is very precariously positioned because if I apply a little bit force on this crystal from any direction, the titanium will get displaced from it is center at the moment. It will be displaced, as the titanium has a high degree of electro positivity; it will actually generate a dipole moment in this crystal. And thus a little mechanical deformation the crystal is charged. And if you imagine that in any bulk material, there are hundreds or millions of crystals, each one of them will get charged because of this deformation.

Although the dipoles could be random and you need to electrode it to make it especially moving towards a particular direction, but those are the things I will talk about at a later stage now; this is about the barium titanate structure. The similar piezoelectric effect you will be able to see in lead zirconate titanate, PZT in the lithium niobium family, in the lead niobium family, in yttrium manganese family, and in the ammonium cadmium family.

The thing that would differ maybe the Curie temperature tells us that, beyond that temperature, the piezoelectricity would not be there. So, that is what is the Curie temperature, which you have to keep in our mind that you will not see the muscle the artificial muscle that we are trying to build in action if the temperature goes a particular beyond a particular level.

(Refer Slide Time: 32:04)



Now, what is the constitutive equation of such piezoelectric structure as I told you that for the direct effect where you are applying mechanical stress, X.

So, you are applying stress in the crystal means increasing X. And as you are increasing X, you will see that the charge is appearing in the system; if you apply or increase the electric field, then also there will be a charge appearing, but that is pretty common is not it for a capacitor type of material you know things like a dielectric material.

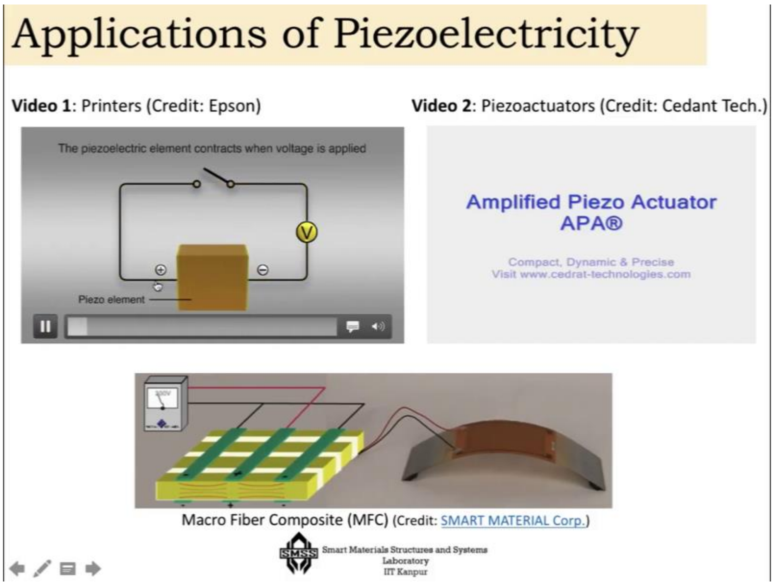
So, that is not what the smartness is where you are applying the mechanical stress and getting a charge out of it; only a very few groups of materials will show these. And the degree up to which it will show is governed by this *d*, which is the electro mechanical coupling coefficient. The higher the *d*, the more will be the electric charge that will be generating in the system.

How can we use this that you are applying stress and you are finding charge will they have great use in terms of the development of sensors. So, the direct effect is generally used for sensor development. Now for the converse effect where you are applying the electric field now, not the mechanical field creating x that is the mechanical strength is quite natural for any material.

But you are applying an electric field and finding the mechanical strain that is something new is not it and that is what is the basic you know equation that we will be using for developing these artificial muscles and by applying electric field mechanical deformations and that is what is the converse effect or the reverse effect the electrical stimulus creating the strain.

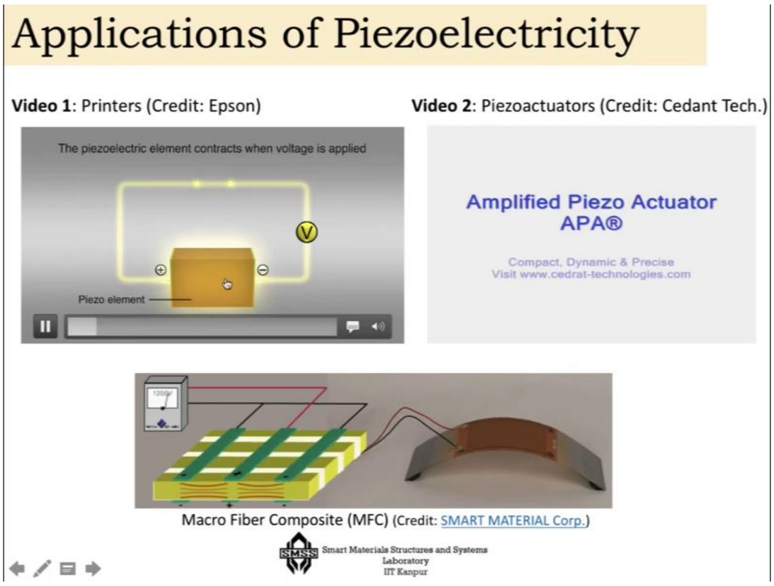
Once again, here, you can see the same electromechanical coupling coefficient. That means the more the materials *d* will be; the more will be getting the strain out of that same electric field. So, these are the two elementary equations that will continuously guide us in terms of the development of actuators and sensors by using these two effects.

(Refer Slide Time: 34:37)



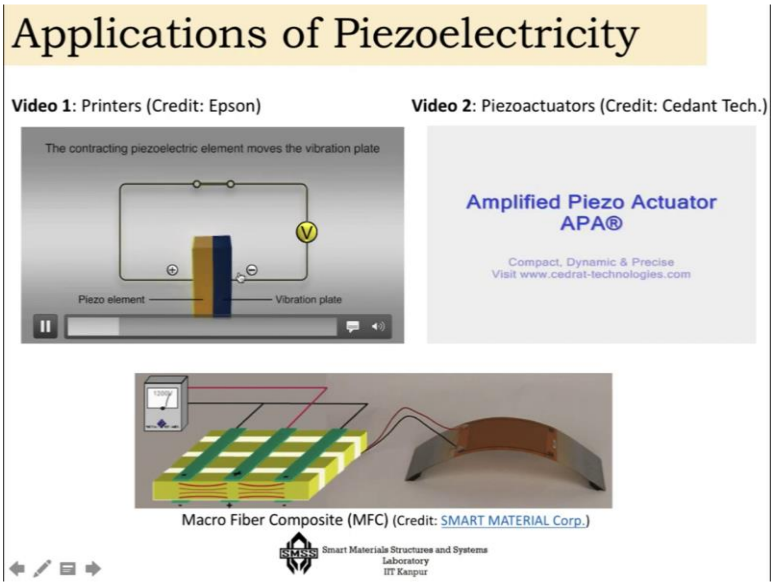
I will now show you some applications of piezoelectricity. The first application as an actuator is pretty standard in terms of every day you might have seen it but might not have noticed that is in printers.

(Refer Slide Time: 34:55)

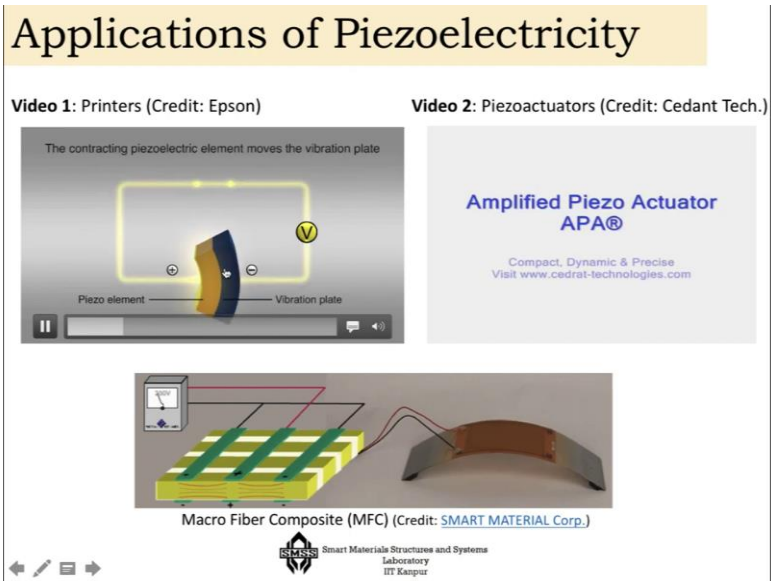


One smart one nonsmart like these two things together, one can make a bending.

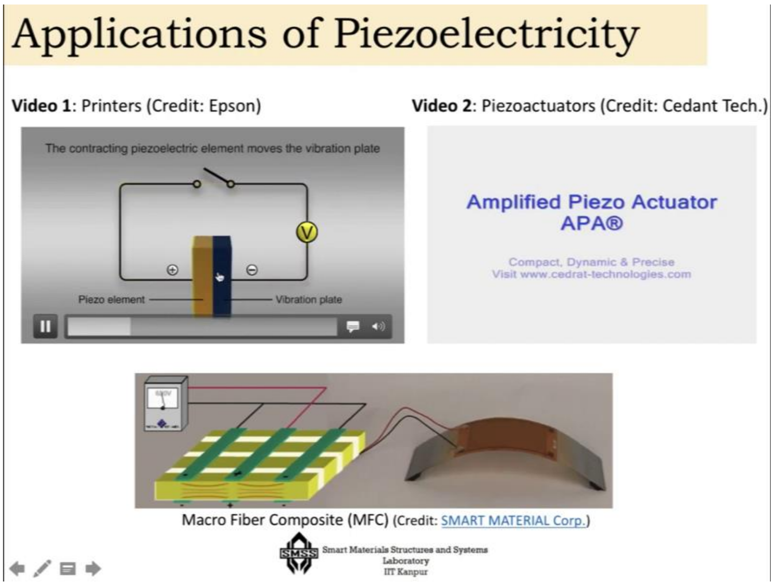
(Refer Slide Time: 35:04)



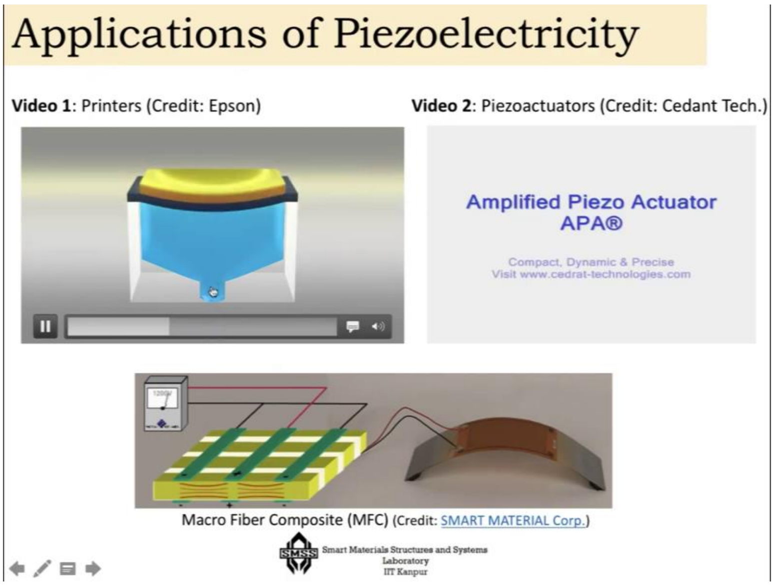
(Refer Slide Time: 35:05)



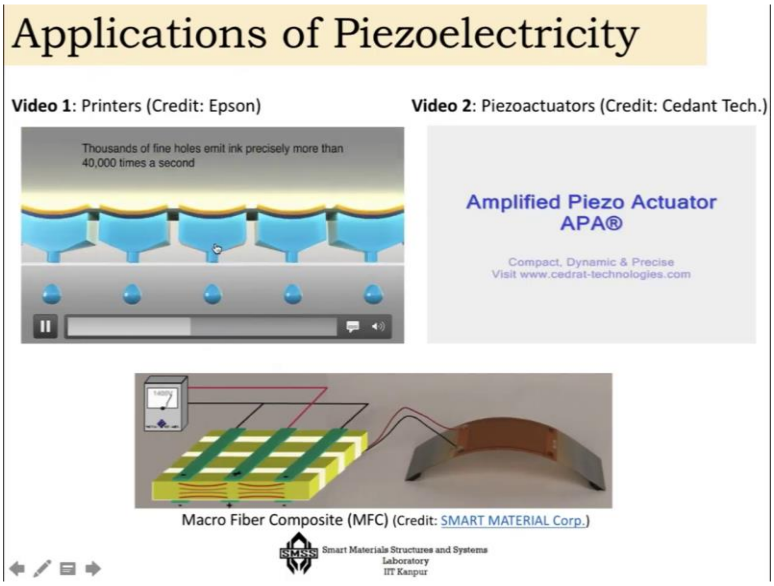
(Refer Slide Time: 35:06)



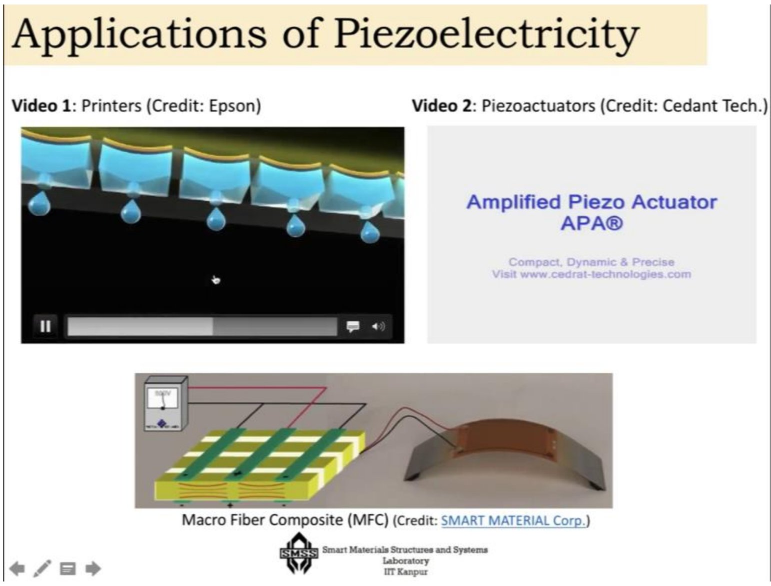
(Refer Slide Time: 35:10)



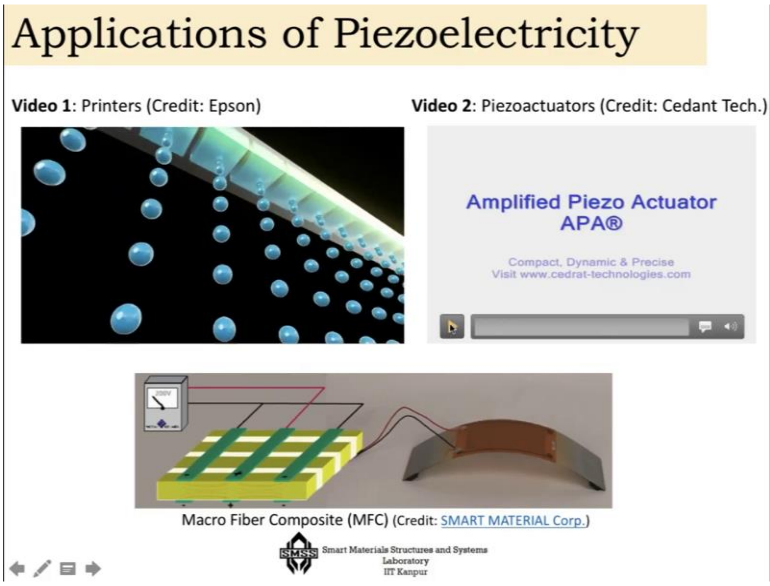
(Refer Slide Time: 35:16)



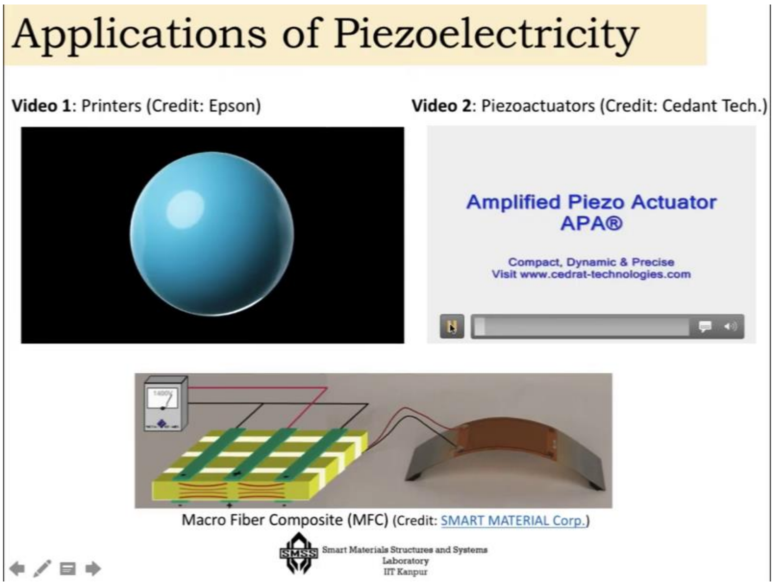
(Refer Slide Time: 35:21)



(Refer Slide Time: 35:26)

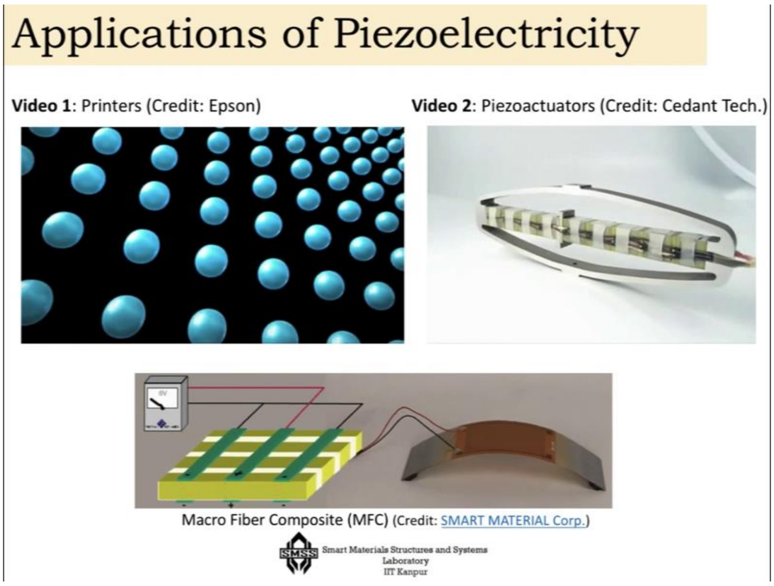


(Refer Slide Time: 35:29)



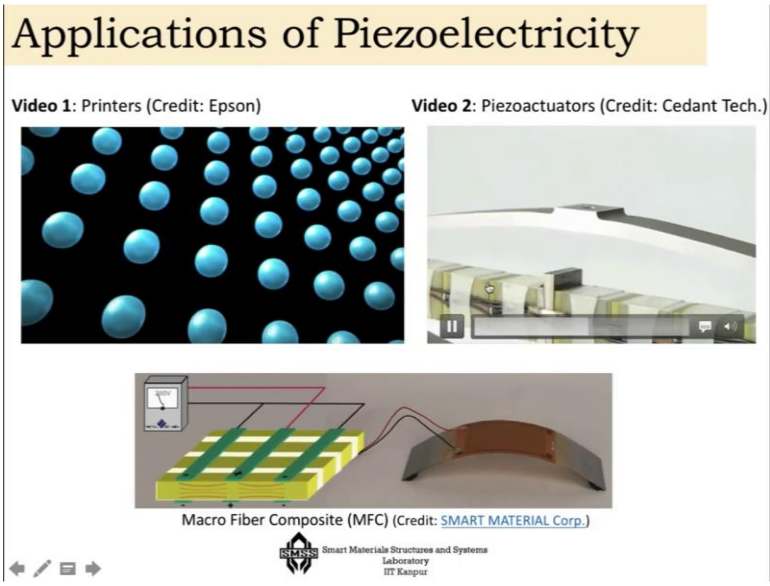
So, this is one application another application is in terms of amplification of the piezo actuator.

(Refer Slide Time: 35:32)



So, if we look at the piezo actuator here, the central part is where the actuation is taking place.

(Refer Slide Time: 35:40)



And this actuation in the central part is very small, but because we have used a unique acolyte structure, a little bit of deformation here can create a large deformation. And all the semi-minor axis of the ellipse, which is what is these amplified piezo actuators do.

And look at the very last one; this is where the piezoelectric material is not offset with a composite. Here also because of this offset by actuating these, you can get a large deformation out of the system. All these three things you can use somewhere or the other in terms of developing the actuators.

So, in this talk, I have told you about one basic block of a smart material, which is the piezoelectric material, and how this piezoelectric material can be used in terms of development in an actuator. And this actuator entire can be used to replace those servo motors that I have showed you in that ASIMO and to make a robot more organismoid or organic like a robot there are many other smart materials. And in the next few lectures, I will quickly cover some very prominent smart materials to you.

Thank you.