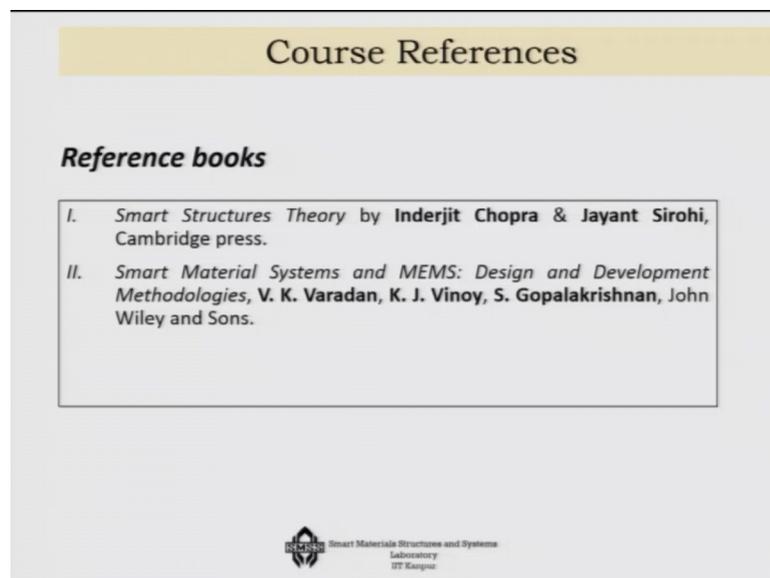


Smart Materials and Intelligent System Design
Prof. Bishakh Bhattacharya
Department of Mechanical Engineering
Indian Institute of Technology, Kanpur

Lecture – 01

Welcome to the course on Smart Materials and Intelligent System Design. This is a MHRD sponsored MOOC course, in which we will be talking about the realm of smart materials and how to build up intelligent systems using smart materials.

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So, in this particular course we will be following these following books Smart Structures Theory, by Inderjit Chopra and Jayant Sirohi, which is from Cambridge press and also Smart Material Systems and MEMS; Design and Development Methodologies by V. K. Varadan and K. J. Vinoy and S. Gopalakrishnan, which is from John Wiley and Sons. Both the books will be required for different parts of the course, which I will be explaining and at these particular places, whenever it will be required I will mention that which text book will be relevant to you.

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4 Week Course Plan

- One Assignment per week: Total 4 Assignments
- Final score will be calculated as : 25% assignment score + 75% final exam score
- 25% assignment score is calculated as 25% of average of Best 3 out of 4 assignments
- Final score will be evaluated for those learners who will opt the final exam.
- E-Certificate will be given to those who register and write the exam and score greater than or equal to 40% final score.

Now, this is what is the course planned in terms of how you will run the assignments. We will be having one assignment per week. So, total there will be 4 assignments. Final score will be calculated on the basis of 25 percent of these assignments score, plus 75 percent of the final score which is optional. Now, 25 percent assignment score will be calculated based on 3 out of 4 assignments, best 3 out of 4 assignments.

And the final score will be evaluated for those who will opt for the final exam; we will issue the E-certificate for those we will register and write the exam and whose score will be greater than, or equal to 40 percent of the final score. So, I encourage all of you to register for the course and also to get a certificate for the course, because that will be important for you for future activities in this very important area.

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Course Content	
Module No.	Title
1	<u>Overview of smart materials</u>
2	<u>An introduction to composite materials</u>
3	<u>Mechanics of composite materials</u>
4	<u>Modelling of smart materials</u>
5	<u>Actuators and sensors based on HBLS (High Band Low Strain) smart materials</u>
6	<u>Intelligent devices based on smart materials</u>

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Now, the course content also let me talk very briefly about it, that is this particular course, I have divided it into 6 sections. In the first section we will talk about the overview of smart materials, in which I will talk about various very common we used smart materials, like piezoelectric materials, magnetostrictive materials, shape memory alloys electro active polymers etcetera. So, we will get fast and overview of all this materials

Next I will be going to composite materials. The reason being, whenever you will be developing intelligent devices you have to embed these smart materials into composites. So, you have to know what is the composite, how a composite is made and, what are the basic governing equations of analyzing a composite system. So, that is why I will first give you an introduction to composite materials and, I will talk about the mechanics of composite materials. Now, once we have a fair idea about these two topic, then we will apply our knowledge of smart materials in terms of the modeling of smart materials. So, then you will see that how the constitutive relationships of smart materials can seamlessly go inside the mechanics of a composite system.

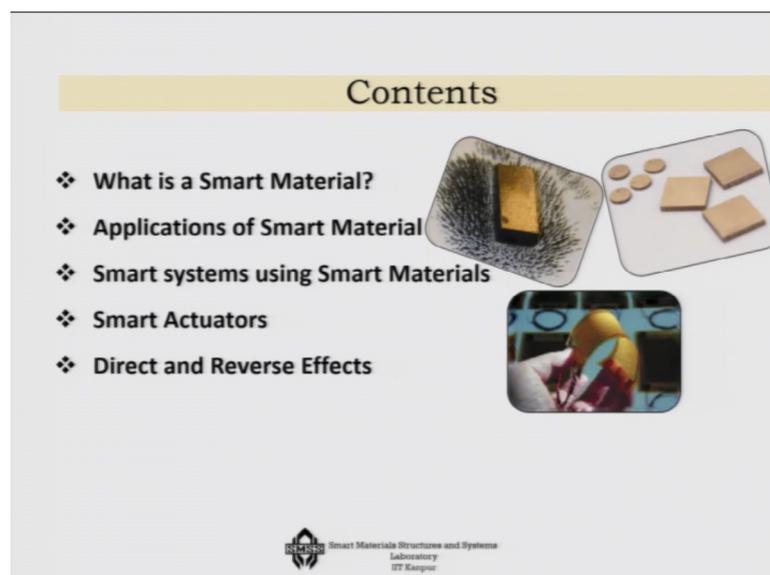
Now, once we have gained the experiences in this first four topics, then we will go into the building up of intelligent devices. To do that our first step will be to talk about actuators and sensors, which are based on HBLS which is: High Band Low Strain smart materials. So, smart materials are generally categorized into two groups, one is a high

band low strain and another is low band high strain. So, what do you mean by high band low strain is that, for high bandwidth it has a high range of frequency, particularly it can go up to gigahertz range which means as sensor or as actuator it will be a very very fast system.

On the other hand low strength signifies that as actuator the deformation that will happen to the system will be low, but you can exploit it as I will be explaining later in terms of large forces. And there are some other group of smart materials which are of low band; that means, their range of frequency available is smaller, but they can give you high strain. Some of the examples of shape memory alloys and electro active polymeric materials, like you know again polymeric shape memory alloys SMPC, call it shape memory polymers. So, I will talk about them additionally when we will first talk about HVLS after that I will just briefly discuss about it.

Next we will come to the concluding part which is intelligent devices based on smart materials. So, how to actually develop intelligent devices using these smart materials; so, this is what will be the course content and in the first week, we will first focus on overview of the smart materials. So, let us begin with the introduction of the smart materials.

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What we will be talking about in this lecture is first of all what is a smart material and, then we will talk about the applications of smart material and, how can you build up

smart systems using smart material, we will also talk about little bit about smart actuators and if time permits about direct and reverse effects. So, the first question is that this very fundamental to this particular course is: what is a smart materials, or what not a smart material.

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The slide is titled "Features of Smart Materials" and contains four bullet points. Handwritten red annotations include: "uni-functional" next to the first bullet point, and two circles containing "strength" and "hardness" next to the second bullet point, and "Capacitor" and "magnetic effect" next to the second and third bullet points respectively.

Features of Smart Materials

- ❖ These materials are a part of a group of materials broadly known as Functional Materials. *uni-functional*
- ❖ The basic **energy** forms that gets **interchanged** are: thermal energy, electric energy, magnetic energy, sound energy & mechanical energy. *strength*, *hardness*
- ❖ **Analogous to Biological Materials:** adaptivity, cellular function, self sensing, actuation & control. *Capacitor*, *magnetic effect*
- ❖ Smart sensors & actuators are highly embeddable.

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There are certain tell tale features of a smart material first of all smart materials belong to a group of materials, which is broadly known as functional materials ok. So, the term is likely misnomer, does that mean that materials are generally they do not function. Well, it is not exactly like that; what it means is that, generally materials are uni-functional. For example, when we explore a particular material, you know we look for some uni-function you know uni-function like say for example, strength.

So, this is one of the important thing in mechanical engineering, that we you know search for materials which gives us high strength ok. Then similarly we can choose materials which gives us a conductivity, be it electrical conductivity, be it thermal conductivity, we can choose materials for that. We can choose materials, which can give us hardness; we can choose materials which can actually give us certain electrical properties. Say for example, you know you can use them as the capacitor, or you can use them as inductor. We can also you know search for materials which can give us a certain magnetic effect, or you know electromagnetism etcetera.

Now, each one of them are unique function, but if some of these mechanical properties get actually coupled with some of these electronic properties, then what we get are actually functional materials. And smart materials indeed have this kind of coupling between mechanical and electronics properties of a material. The other way to look at it is that what are the energy forms that get is interchanged in such material, because in every material whenever we apply say for example, a mechanical force to the system, then the force many things can happen, but the major part of the force may go to deform the material, which means the energy will be stored inside the material in the form of strain energy which is a mechanical energy.

But suppose the material gets heated, then that interchange is in terms of thermal energy, suppose it also generates voltage, then that mechanical energy get is interchange to electric energy. Suppose it generates a magnetic field magnetic energy sound energy of course, and vice versa from electrical energy to mechanical energy. So, all these interchanges if a material allows not every material would allow such a thing, we would later on see that certain crystal structure only promote his kind of interchanges of energy. So, that is another tell tale sign of a smart material.

Then the other interesting feature is that this materials can be actually designed in a manner that become adaptive, they become cellular in function, self sensing they can sense you know and they can actuate on their own and, they can control themselves. All these properties I will unfold as we will discussed about smart materials, but very briefly what adaptivity means is that as the environment changes can the material change it is behavior based on the environment like, I will show you a particular material which as the temperature changes, changes it stiffness which is known as the shape memory alloys.

The cellularity in function actually means that just like biological systems, where every cell works a in a kind of an autonomous way, you can store them and you can keep them alive even if you can detach them from a particular living system, for some time. So, that is the capacity that it every cell has a degree of autonomy similar to that, whenever we will be having a smart device you will see that every smart material unity need, because it is this powers are derived from the atomic structure, or from the molecular arrangement. So, at a very small scale level they are actually cellular in nature so, that is why they are analogous to biological materials.

And finally, which is why I am talking I will be talking about composites you know as soon as we talk about smart materials, that these materials the moment you know put it inside another structure it becomes a composite structures and, that is the capacity of this material they are highly embeddable in. So, an nut shell that if a material belongs to be functional group, if a material has the capacity to interchange the energy, if it is you know kind of adaptive and cellular in terms of it is nature. And, if it is highly embeddable can say that yes these are the features that makes the smart material. So, when we say smart so; that means, there must be a scale in terms of the smartness now what happens if something is not smart at all ok.

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Smartness in a scale of intelligence

- ~~Stupid~~ – ~~Dumb~~ – ~~Foolish~~ – ~~Trivial~~ – ~~Sensible~~ – **Smart/Clever** – **Intelligent** – ~~Wise~~
- Present smart materials are in the range from highly sensible to poorly intelligent level.
- Passive smartness to Active Smartness; eg. of passive smartness - multiphase rocket nozzle of Space Shuttle.
- Porous Tungsten with silver coating, Graphite, Ceramic Layer, Steel
- Passive smartness is in open-loop!

Passive Smartness

- Lack the inherent capacity to transduce energy.
- Can act as only sensors but not as actuator.

Other example: Optical fiber cable

Temperature, pressure, mechanical strain → **Optical Fibre** → Change in Opto-Electronic signals

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So, the way we call oak valley say of say you know somebody, or something is not we say that stupid. And maybe a little better than stupid as per dictionary is dumb, or may be little better is foolish, little better is trivial, little better is sensible. Now, the degree of smartness starts from the sensible point onwards; that means, it is smart or clever even if it is better than smarter clever, then it will be intelligent.

And if it goes beyond you know the common level of intelligence that occurs, which is what is the future of all this materials is that can the materials themselves, or the systems that we can build using the material the wise. So, which is a you know distant future that if it can happen a in reality. But this is what is the direction in which we are trying to develop materials which becomes more and more and more intelligent, the present smart

materials are actually the range of highly sensible to maybe poorly intelligent level ok, that is the range in which our smart materials are currently placed.

Now, this kind of highly sensible to poorly intelligence, how do we range how do we say that a particular smart system is highly sensible, or particularly smart system is more than sensibility smart, or it is intelligent etcetera. It actually starts from passive smartness to get a highly sensible material by passive smartness, what do you mean is that it has a limited capacity to deal with the change of environment, but that capacity also is actually pre jazzed you cannot really change that capacity as the environment suddenly changes. So, that is like our passive smartness.

One of the examples that I always give is the multiphase rocket nozzle of space shuttle, if you look at a space shuttle, you will see that the structure of a space shuttle is a very complicated, you know system, it has actually multiple levels of materials in, it starts with porous tungsten with silver coating, it has graphite it has ceramic layer and it has steel. So, each one of them are actually meant for certain particular function, like the porous tungsten with silver coating gives it high temperature as well as you know, because it is porous the tungsten it gives less thermal space concentration.

If I add graphite to it i get higher temperature resistance, if I add ceramic we add to it I get even higher temperature resistance, because the tip of this particular space shuttle is subjected to something like close to 1500 to 1600 degree centigrade of temperature. So, you need to have this three systems fighting this high temperature as the temperature increases more and more, the porous tungsten graphite and all these layers they actually help in terms of this high temperature.

But inside dip inside what you have is steel, which is needed for actually, because steel is machinable so, all the equipment that you will be having inside the system you know in the steel part actually helps in terms of joining them with this structure. So, that is why it is needed. So, this is a sensible design where you have thought of that as a special tool is going, or it is coming back to earth what is the different level of temperature pressure that it will be undergoing and, you have designed a structure beforehand thinking of all these various possibilities.

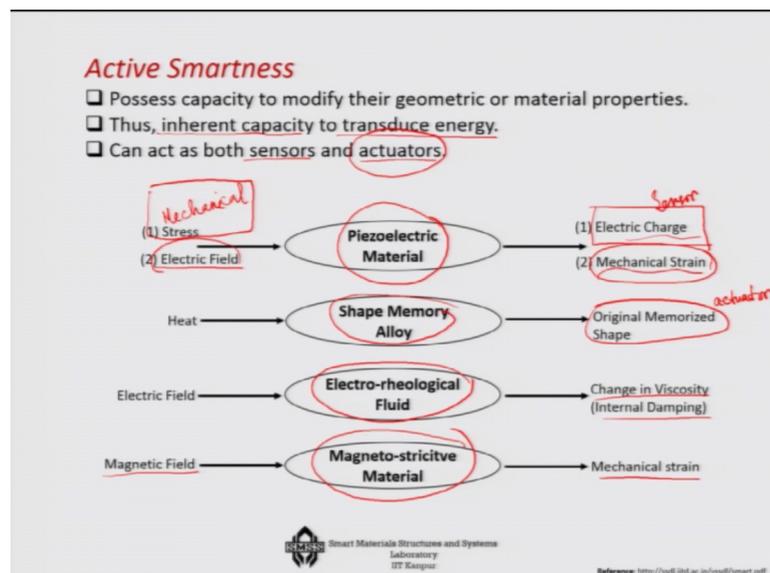
However, the problem is that this is an open loop structure, what if my space shuttle does not enter earth, what if you know you know by chance it has to be targeted to moon, or

some other you know planet, then this you know system may not work. Because, this system is precisely design for the for leaving earth and for reentry in the earth based system. So, then in such cases the passive smartness fails, you need some kind of an adaptivness in the system. So, passive smartness lack the inherent capacity to transduce the energy, because it can only convert the energy to a particular form, it can act only generally as sensors, but not as actuator and so, you need an active system.

Another example of a passive system is this optical fiber cable, if you ever see this TV cables if you actually cut this cables, you will see that it has several layers it has a core layer, which is actually tire swatting the optical signal actually, then it has a cladding which actually helps the signal to remain inside the core itself the refractive index is designed in such a manner. Then it has a buffer coating which actually helps the system to not to get exposed to the ambient weather etcetera.

So, once again this is design considering a particular range of temperature pressures etcetera, what if these things changes, then the optical fiber has to get that kind of an adaptiveness into it. So, this is what is the smartness; in a scale of intelligence that we are looking for that can we make it more adaptive like an active smartness.

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Now, when we talk about active smartness, we talk about a material which process the capacity to modify either they are geometry, or they are material property. So, add it definitely as I told you earlier that it must have the inherent capacity to transducer the

energy. Now, if you look at it that if you get these properties, then you can actually design it a manner that it can be acting both as sensor, or as well as actuators let us give some examples, one example is this piezoelectric material I will talk about all these materials later on, but let us you know first of all take the names with us that there is a group of material call piezoelectric mechanical, if I apply mechanical stress so, this stress is mechanical in nature.

So, if I apply mechanical stress in this material, the I am going to get electric charge as well as the mechanical strain. Again if I apply electric field to the material, I will be getting electric charge as well as mechanical strain. So, which means I can use this material in terms of either using electric field I can generate mechanical strain, then it will be working as an actuator, or I can use mechanical stress. And I can find out what is the electric charge that is generated we will be using it as a sensor. So, you can used both as actuator as well as sensor.

There are other materials which cannot be used as both sensors and actuators like shape memory alloy, if you look at it if you apply heat, there will be a geometry change in the system. So, that geometry change can we actually used in terms of generating mechanical forces. So, in this case you are using a non mechanical input and, you are getting a mechanical output from the system. This kind of things can be used in terms of them building it as an actuator.

Again in another case you can actually changes the material property not the geometric property like, if you consider the electro rheological fluids, if you apply electric field as an input you will see that the viscosity of the system changes. So, there is a change in viscosity, and that will change the internal dampings etcetera so, this is very much used in terms of what you call you know suspension system designs in mechanical systems.

If you use magnetic field as an input, then there are materials which are known as magneto strictive materials, they transduce and they actually generate the mechanical strains. So, this is another group of material with an another capability of transduction of energy. So, they are all like that many other transductions that we will be actually summing up in a matrix soon.

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Traditional v/s Smart System

Traditional system

- Designed for certain performance requirements e.g. load, speed, life span.
- Unable to modify its specifications if there is a change of environment.

Smart System

- Can accommodate unpredictable environments.
- Can meet exacting performance requirement.
- Offer more efficient solutions for a wide range of applications.

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So, you will see that what are the other possibilities that is there. So, let us assume a big comparison at this moment between a traditional system and a smart system, as exactly we have discussed earlier that traditional systems are design for a particular performance requirement, in terms of load speed, or life span they are unable to modify their specifications.

If there is a change of environment, on the other hand smart systems can accommodate unpredictable environment, they can meet you know this performance requirement of course, and they offer more efficient solution for a wide range of applications that is why they are so, popular today.

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Smart Materials

Smart Materials are those which possess ability to change their physical properties in a specific manner in response to specific stimulus input.

Commonly used smart materials are:-

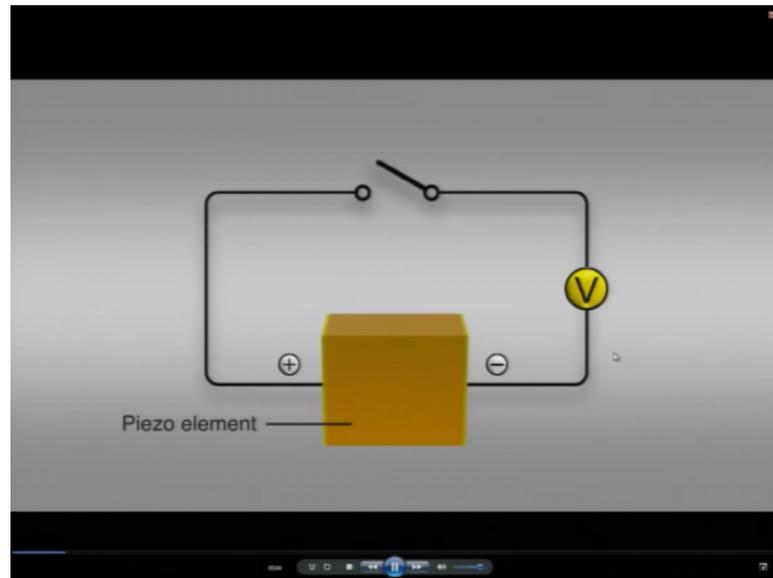
1. **Piezoelectric** - Generate an electric charge in response to applied mechanical stress and vice versa. (Video- Epson Printer Application)
2. **Magnetostrictive** – Change in dimension of ferromagnetic material in magnetic field and vice versa.
3. **Phase-Transition dependent** - "Remembers" its original shape and after being deformed returns to its original shape when heated.
4. **Electro/Magneto Rheological Materials** – Change in viscosity in response to electric/magnetic field.

Image: Wikipedia

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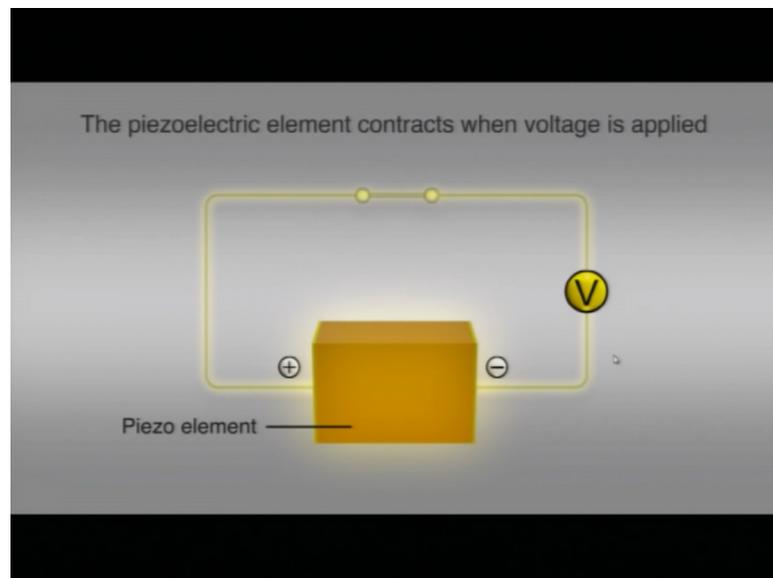
If I try to now define that what is smart materials are those which possess the ability to change their physical properties, in a specific manner in response to specific stimulus input. So, this is important that they are able to change their physical properties, in response to specific stimulus like I told you that piezoelectric material is one such smart material, which can actually generate an electric charge in response to applied mechanical stress. And also it can actually generate mechanical strain in response to the application of electric field. Let us look at an example of you know how you can use this technology. So, if you look at you know you all of you must be acquainted with the printer.

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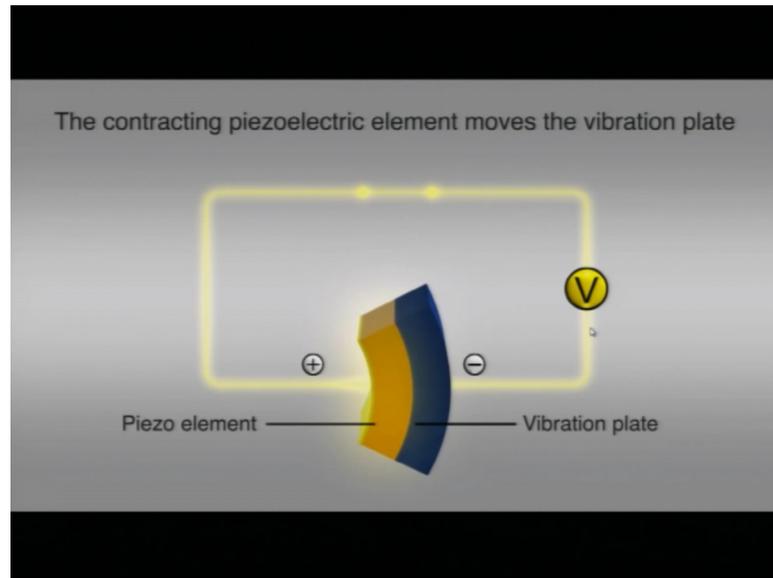
So, how does a printer work, if you look at that what you will see is that the printer basic technology is actually based on smart material.

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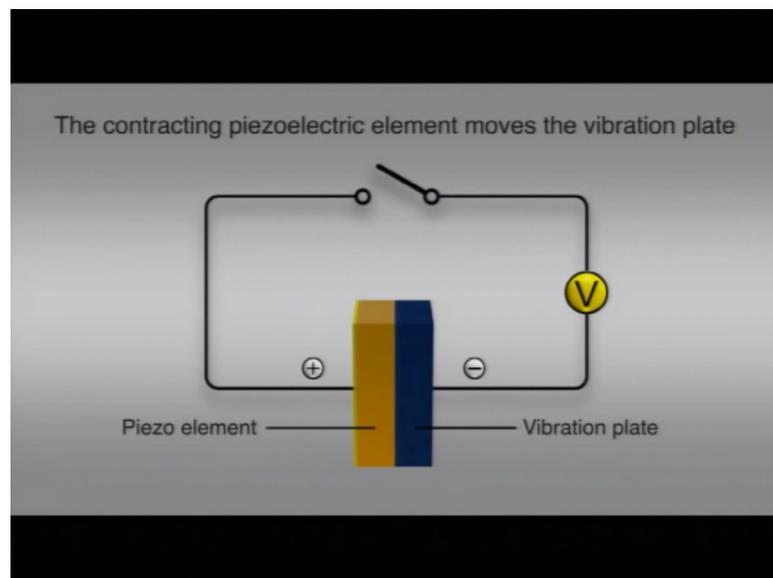
There is a Piezo element in each printer, which if I apply voltage to it expands, or contracts are you can also by editing an in art material.

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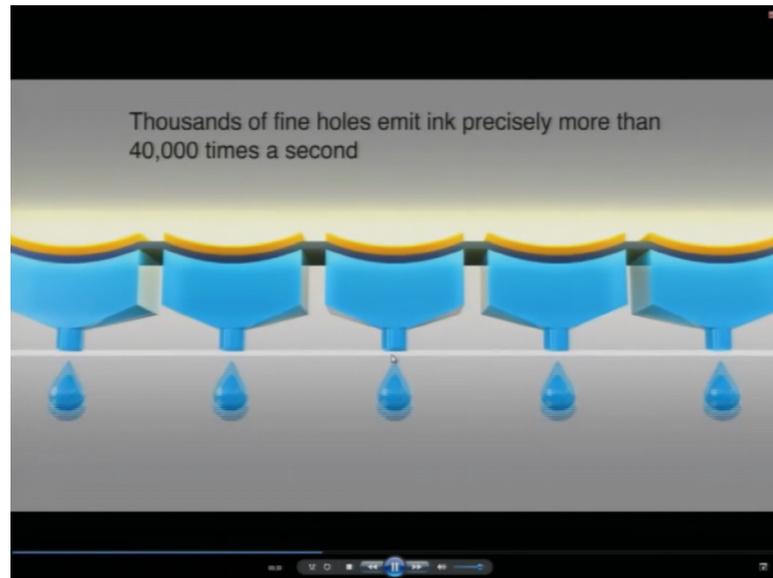


You can also bend it through whatever direction you use now, you see.

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That you are bending and as the result is giving pressure as the result you are controlling the fluid flow, if there are thousands of them that is what it is there in any printer, they are controlling the fluid flow essentially of various colors.

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Now, you see these are controlling this fluid colors and that is what is arranging themselves in an array and all these arrays, in their layers together is actually giving you a particular print that will come up. So, essentially you can see that in any common

printer, this is: what is the technology behind the printer, that it essentially uses piezoelectric material to implement this kind of a printer operation.

Now, if you look at another smart material, which is called magneto strictive material, it has actually change in dimension it happens mostly in ferromagnetic materials due to magnetic field and vice versa. So, there are some ferromagnetic material and their impact some materials where this effect is too prominent actually. So, these are magneto strictive materials where the magnetic field can a you know affect this change. So, the last change that we have seen in piezoelectric material, they are the change is happening by elect the application of the electric voltage, where is here it is by application of magnetic field. There are some materials like phase transition dependent materials like shape memory alloys, they can actually remember their original shape.

And after being deform, they would return to their original shape, I will show you in this course sometime that how in our laboratory, we use the shape memory material for actuating different systems. Now, there is another material which is electromagnet rheological material I told you, which actually changes is viscosity in response to electric or magnetic field, like as you can see in this particular case, that if these electric field is not applied the fluid is flowing if the electric field is applied it become viscous that it does not flow.

So, the idea is that if I can you know make almost like say a super viscous material is what it is like glass. So, if I can make a material super viscous it will behave almost like a solid material, in that case it will be you know able to transfer mechanical forces like a clutch system, if you think of it that you know it will work like you know that it will be able to transfer the mechanical power. But if I you know withdraw the electrical energy, then it will become once again fluidic and; that means, you know it will be isolated the two systems, you know which joined by it can be suitably isolated by this particular way.

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Why smart sensors and actuators ?

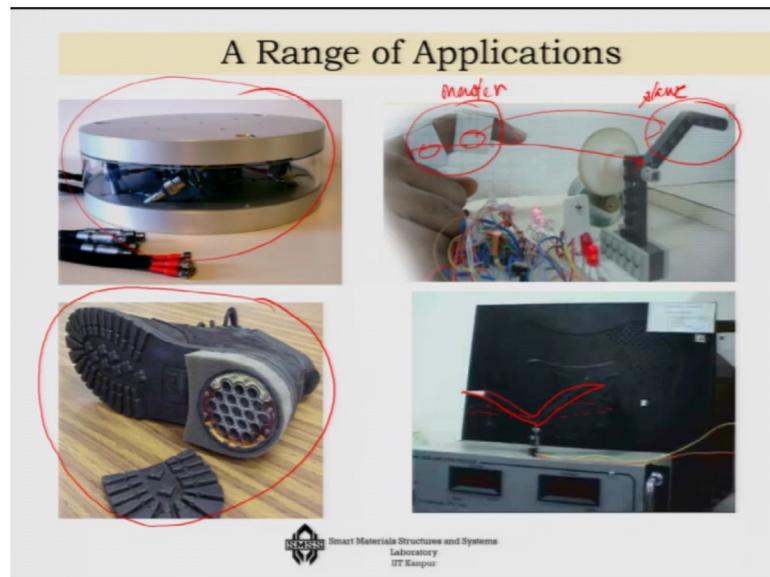
- Real time response
- Exploit functional properties
- Better embeddability
- Minimal effect on structural properties
- Reduction in weight
- Less power consumption
- Better reliability

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So, these are you know various examples of the smart material so, why are we so, keen on studying the smart materials, because you can make sensors and actuators out of them and what is the what is so, important about such sensors and actuators a they are very fast. So, you get the real time response; that means, there is no delay you put the material immediately you will start to get you know the response of the system, you can exploit various functional properties of the material by using this, it is embeddable also.

So, you can put it into a structure very nicely so, that you know you are not attaching something attach externally, it gets you know very seamlessly integrated into a system. It has minimal effect on structural properties. So, it is reasonably good structural properties on it's own and in fact, many of them light. So, quiet light so, there we will get a reduction in weight and if you compare them with the traditional system, there will be much less power consumption and it has a much better reliability as a system.

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So, if I actually look at range of applications, some of them a laboratory waste some of them are actually already commercially available, like the first example which is an isolator which is used for space applications, this is where a smart material is used all also energy generator this is where a smart material is used these are commercially available.

Some of the technologies we are developing laboratories like, this finger you know whatever it is doing, the robotic finger is trying to simulate. So, we call it as a master to slave training and that is possible, because of the smart materials that are there which are actually sensing the change of strain, communicating it to the system and that you are getting exactly the slave performing the same way, this is something which we feel will be very useful for telly surgeries.

Then also there is something like you know you maybe in to follow that there is a wing here. So, this wing which is like a butterfly wing, if I apply an electric field the wing can actually flap. So, you know you can actually develop an insect which can actually flap and as the insect can flap, then you can actually use it for various surveillance activities etcetera.

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Smart Materials for Sensing & Actuation					
Output	Current/ Charge	Magnetization	Strain	Temperature	Light
Input					
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


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So, there are range of such applications possible, now here comes the very important table first ok, that this table will also tell us that which materials are smart and which are not. So, if you look at it that we have the outputs and inputs this is the way the table is arrange, in the input we have considered electric field magnetic field stress means mechanical stress heat and light. In the output we have considered current, or charge magnetic field corresponding to that magnetization, mechanical stress corresponding to that strain heat into that temperature and light corresponding to it light itself.

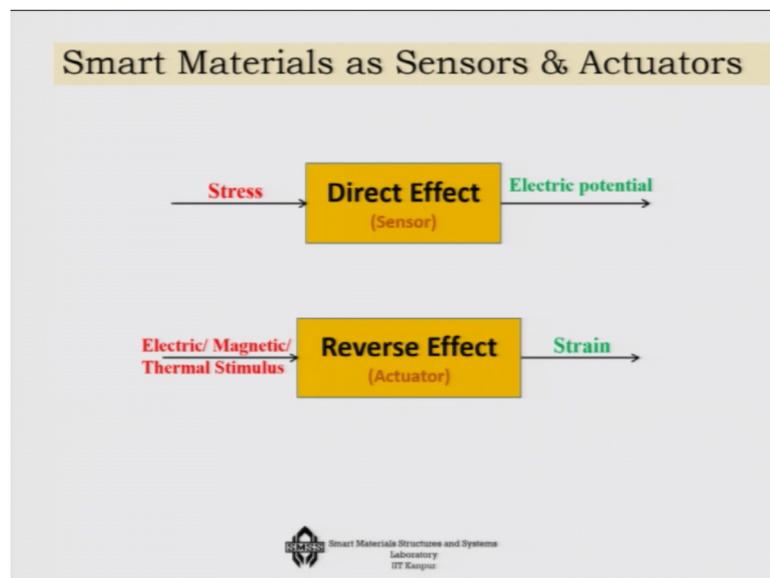
Now, if I look at the diagonals of this particular matrix, if I look at it then if I apply electric field and I actually you know get current out of it, then it is the conductivity that is operational if it is a dielectric material I get charged out of it. So, that is due to the permittivity now that is not smartness whereas, if I apply electric field and I get a mechanical strain which happens due to reverse piezoelectricity. So, any material can be either conductive or insulator insulating in nature that is not smartness, but if in addition to this conductivity, or insulation if the material can generate mechanical strain when I am applying electric field then it is a smart material.

Similarly, when I am applying magnetic field, if this happens along this column the mechanical strain, which is also defined by the Jule effect, then it is smart material. For heat if there is a thermal expansion related to phase transition not a normal thing what a

phase transition, then it is a smart material for light, if the light itself changes the shape, then it is photostriction it is a smart material.

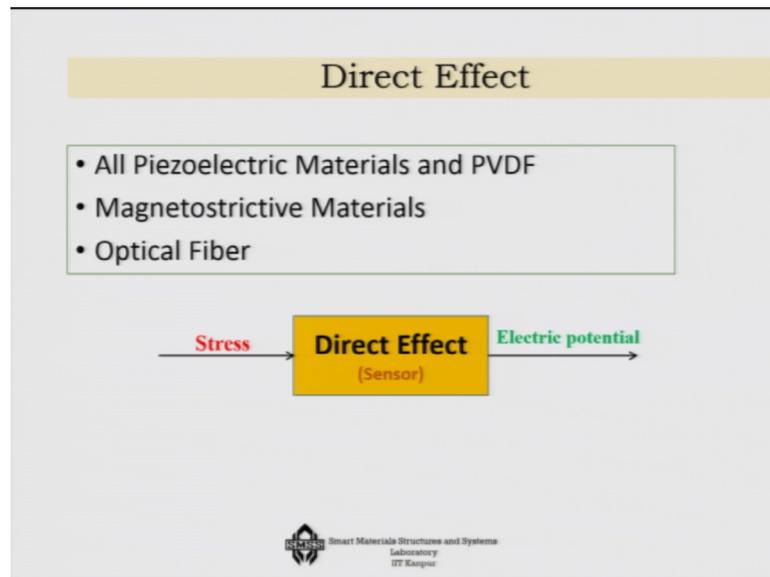
So, this column and so, true is from the other side also if I look at it because this column we will get when we will take the mechanical stress in mind, if I take the mechanical strain in mind then that coupling if I look at it like if electric field related and stress generating direct piezoelectric effect coupling and, again the magnetic field generating the Villary effect. And again temperature thermomechanical effect and light the photo elastic effect, then that is also another set in which we get this kind of coupling in the smart materials.

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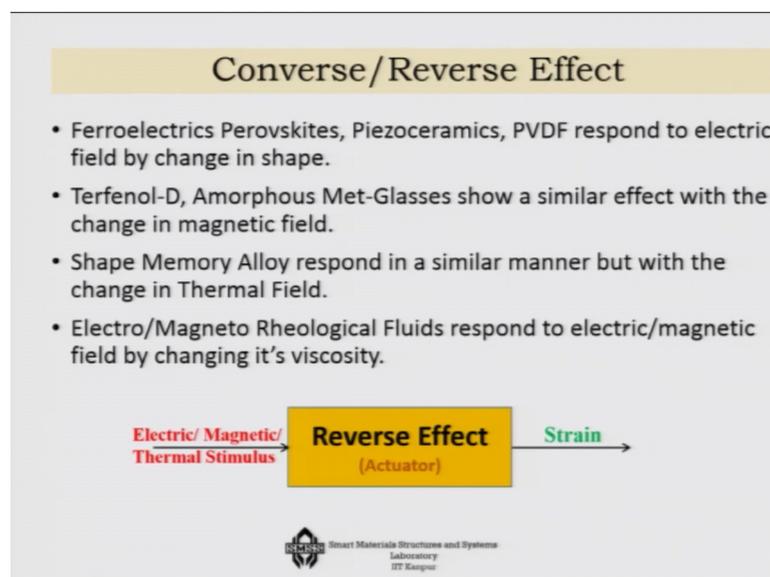
So, we can subdivide such smart materials into two groups, one group in which mechanical stress creates the electric potential. So, this is the direct effect stress, creating electric potential. The other group so, naturally this direct effect is used for sensors, the other group where electric magnetic and thermal stimulus is giving me mechanical strain, this is what is there in the reverse effect or as actuator. So, direct effect is used for sensing and reverse effect is used for actuation purpose.

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What are the materials which shows direct a direct effect will all piezoelectric materials and PVDF magnetostrictive materials and optical fibers, they are also this direct effect; that means, if I apply mechanical stress I will get a change in electric field potential.

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So, we can use such systems for sensing the reverse effect, where we are using a electric or magnetic field or a thermal stimulus to get a mechanical field, so, that mechanical strain. So, that you can use it and actuator there are many materials of course, all piezoelectric materials like ferroelectric Perovskites is a very special structure.

I will talk about it in one of the lectures Piezoceramics PVDFs, they all respond to electric field, then there are group of materials like Terfenol D Amorphous met glass they show similar effect in magnetic field shape memory alloy. So, the effect thermal field and electromagnet rheological fluids respond to electric magnetic field by changing its viscosity. So, these are all categorized in the reverse effect.

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Traditional v/s New Actuators					
Drive	Device	Displacement	Accuracy	Torque/Generative Force	Response Time
<i>Air Pressure</i>	Motor	Rotation	degrees	50 Nm	10 sec
	Cylinder	100mm	100 μ m	10 ⁻¹ N/mm ²	10 sec
<i>Oil Pressure</i>	Motor	Rotation	degrees	1000 Nm	1 sec
	Cylinder	1000mm	10 μ m	100 N/mm ²	1 sec
<i>Electricity</i>	AC Servo	Rotation	minutes	30 Nm	100 msec
	DC Servo	Rotation	minutes	200 Nm	10 msec
	Linear Stepper	1000mm	10 μ m	300 N	100 msec
	Voice-Coil	1mm	0.1 μ m	300 N	1 msec
<i>Smart materials</i>	Piezoelectric	100 μ m	0.01 μ m	30 N/mm ²	0.1 msec
	Magnetostrictive	100 μ m	0.01 μ m	100 N/mm ²	0.1 msec
	Ultrasonic Motor	Rotation	minutes	1 Nm	1 msec


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If I compare between the traditional versus new actuators, we will see that in comparison to the traditional actuators like air pressure, oil pressure, or electricity, if you look at the smart materials you will see that they have generally lower you know strange rangers etcetera, but they have much higher accuracies compare they with the accuracies here ok, or accuracies here much higher accuracies. And also much faster response time that is what makes smart materials to be so, special in comparison to other materials.

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Smart Actuators	
Input Parameter	Actuator Type / Devices
Electric Field	Piezoelectric / Electrostrictive Electrostatic (MEMS) Electro - Rheological Fluid
Magnetic Field	Magnetostrictive Magneto - Rheological Fluid
Chemical	Mechano - chemical
Heat	Shape Memory Alloy Shape Memory Polymer
Light	Photostrictive


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We can classify them in terms of the input parameters like, if the input is electric field, then you have piezoelectric materials MEMS, or air fluid if it is magnetic field magnetostrictive material or magne torheological fluid, chemical mechanochemical effects heat shape memory alloys, shape memory polymer, if it is light is like photo strictive materials.

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Properties of a few Smart Materials				
Properties	PZT	PVDF	Terfenol-D <i>Magnetostrictive</i>	NiTiNOL <i>SMA</i>
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

H.B.L.S
LBHS

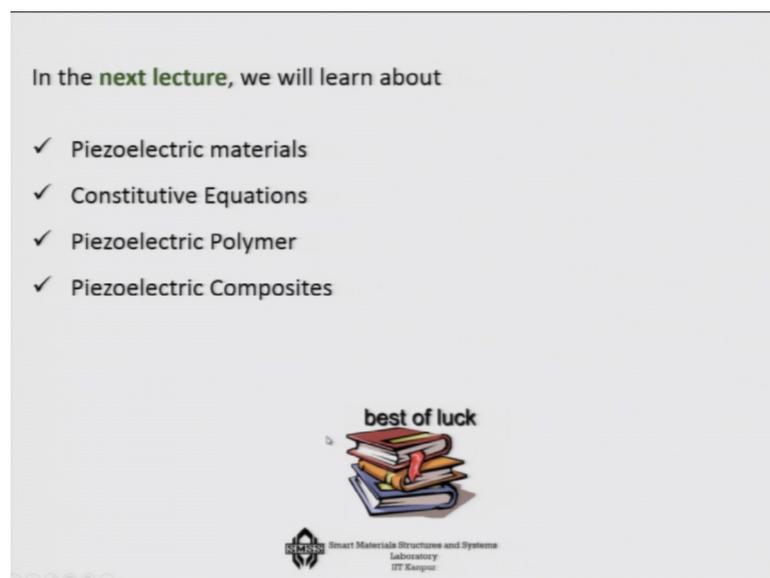

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If I go for you know various properties of these materials one important properties how much strain is happening to it. So, this is known as free strain is there is no other force

just you are allowing it to get default. Now, then piezoelectric materials this is PZT is a piezoelectric material, that shows about 1000 parts per million, which is quite good in the piezoelectric range PVDF little less Terfenol D, this is a Magnetostrictive material I will talk about it this shows actually more mechanical strain, that is about 2000 parts per million and NiTiNOL this is a shape memory alloy so, we call it SMA shortly this shows maximum strain.

Elastic modulus wise all of them are quite good except these PVDF which is little low. And interesting things to notice a 2D alloy has actually two different elastic modulus, it happens due to phase transition bandwidth wise piezoelectric material and PVDF they have the highest bandwidth Terfenol D has the lower bandwidth and the lowest bandwidth is this particular SMA, which we call as low band high strain material and this materials generally are categorized as high band low strain material.

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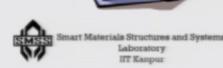


In the **next lecture**, we will learn about

- ✓ Piezoelectric materials
- ✓ Constitutive Equations
- ✓ Piezoelectric Polymer
- ✓ Piezoelectric Composites

best of luck



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So, this is a broad overview of these smart materials. In the next lecture we will talk about piezoelectric materials and their constitutive equations piezoelectric polymers and composites.

Thank you.