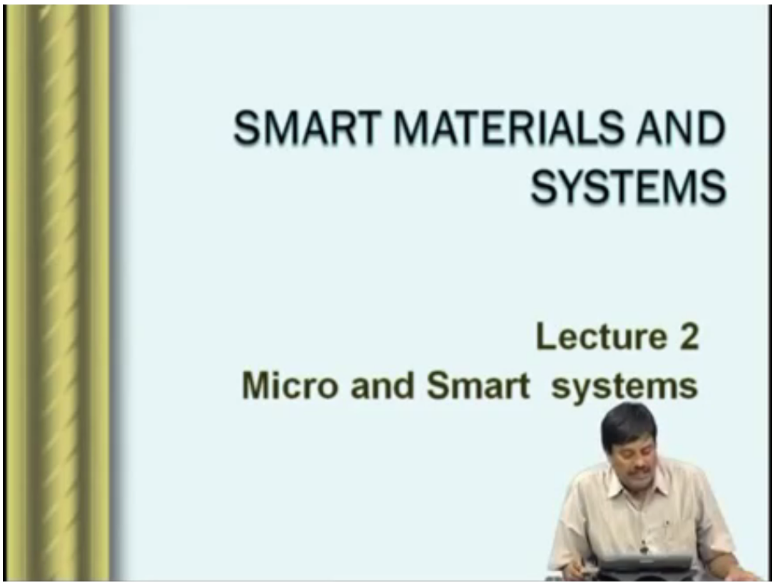
Micro and Smart Systems
Prof. S. Gopalakrishnan
Department of Aerospace Engineering
Indian Institute of Science - Bangalore

Lecture - 02
Smart Materials and Systems

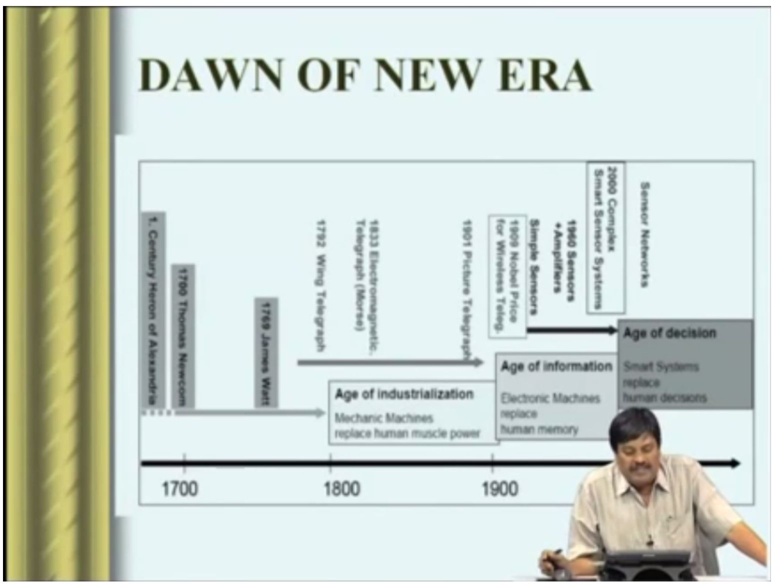
Today we are going to talk on the lecture 2 part of the micro and smart system course and this concerns on the overview of smart materials and systems.

(Refer Slide Time: 00:23)



Before we go into details of what the smart materials and system we will take a look at what are these scientific achievements that the world has made since the beginning of the human civilization.

(Refer Slide Time: 00:33)

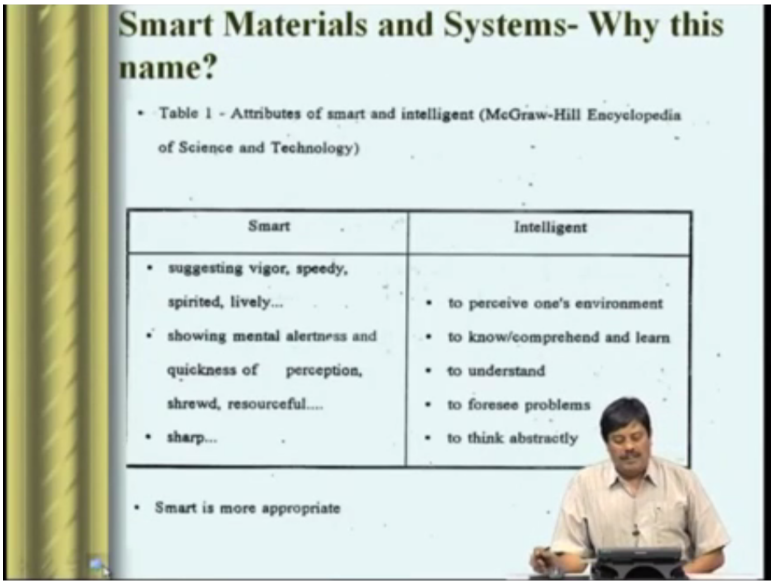


There was absolutely very little scientific activity until 1769 when James Watt invented the steam engine. Since then there are efforts to start to replace the human muscle power from the machines so for which basically the industrial revolution started some time in 1800 and continued up to 1900 and where a number of novel machines were found.

Since 1900 there were efforts to convert the electronic and electrical machines to replace the human memory. So the age of information started some time in 1900 and then close to that in 1909 the first noble prize for the wireless telegraphy was given in 1909. Since then lots of systems that are trying to replace the human memory were attempted and in 1960 number of sensors were developed, amplifiers and in 2000 is what we call the age of information is giving away to the age of decision.

So the whole concept here is the decision can be made by the systems what we call the smart systems rather than by the human beings. So the smart systems and materials has a place in this aspect.

(Refer Slide Time: 02:46)

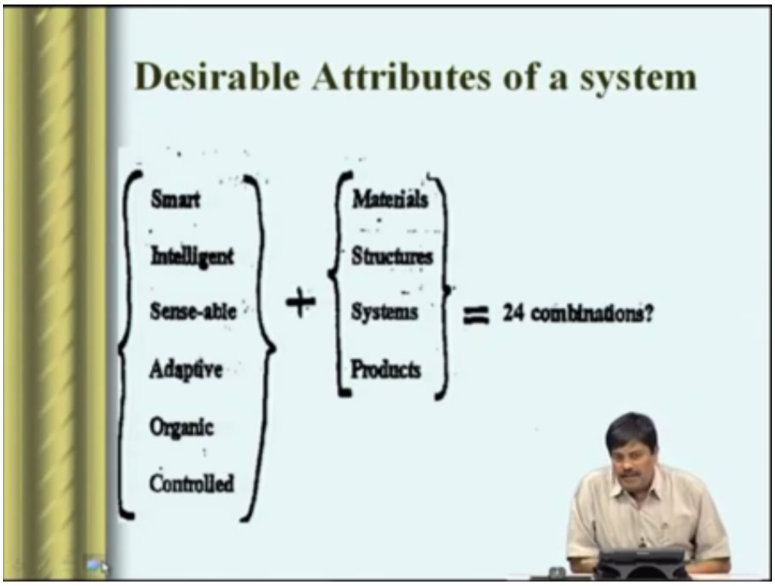


So now what are smart materials and system? Why is this name? If you try to find out the name based on take a dictionary or an encyclopedia you would basically see that, there are a number of meanings or number of definitions that are given to smart. There are 2 things that we can call. Can we call the structure smart? Can we call the structure intelligent? So the smart structures and intelligent structures has totally different meaning.

If you look at the word smart in the dictionary, it says that smart means suggesting vigor, speedy, spirited, lively, the one showing the mental alertness and quickness of perception, shrewd, resourceful and sharp. As oppose to smart definition if you look at what is the definition of the intelligent, it says that to perceive one’s environment, to know and comprehend and learn, to understand, to foresee problems and to think of abstractly.

If you look at these 2 definitions, we want the system obviously to be more intelligent, but that is a lot more challenging. So today if you want to build a system that can do something much better than what is today we want to call it as smart. Hence the smart was a more appropriate definition and hence we call it smart systems rather than intelligent systems.

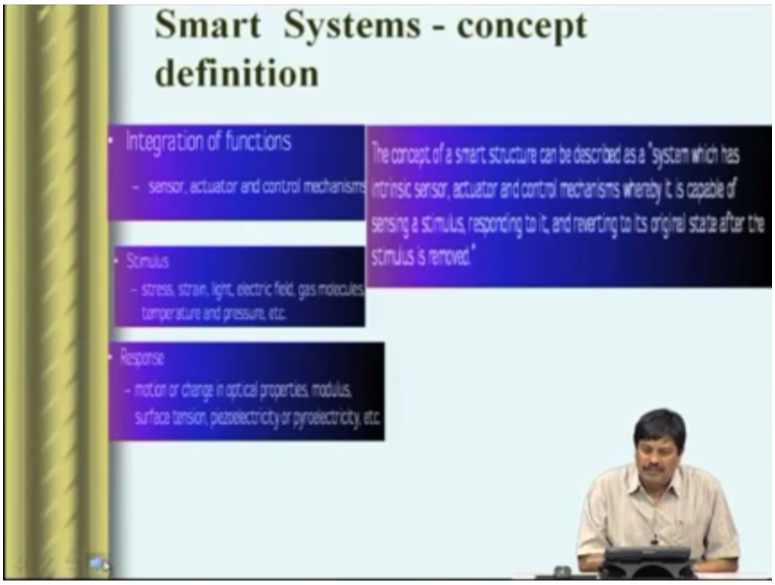
(Refer Slide Time: 04:23)



So now let us go and see what are the desirable attributes of a system? So we want the system to be smart, we want the system to be intelligent, sensible, adaptive, organic or controlled. So these are some of the behavioral aspects that we want a system to have. On the other hand, a system has materials, it has structures, it has systems, it has products. A combination of these 2 will put together a really, really an intelligent system and how many such possible.

There are 24 such combinations are possible and if you have all these things we would really achieve an intelligent system.

(Refer Slide Time: 05:12)

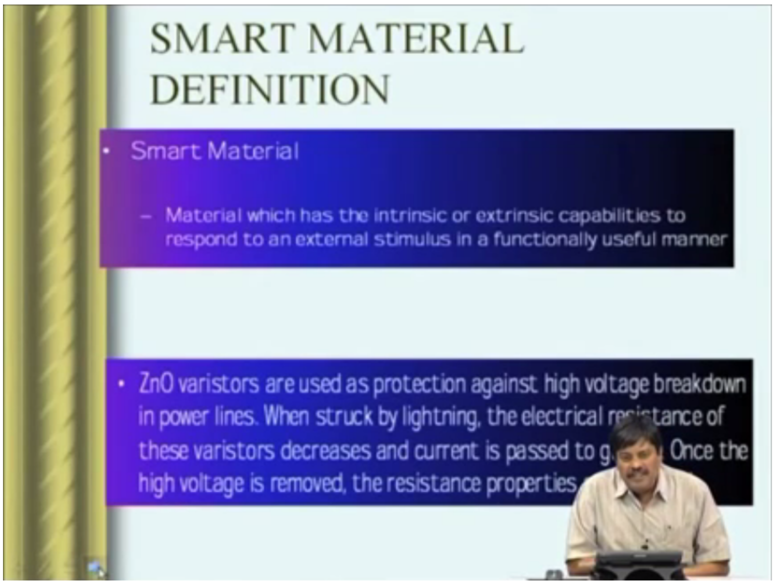


Now let us discuss about the smart system concept per se. So we want a system that is smart so what should it do. So it has to integrate the functions for which it requires sensors, which is made of certain materials called the smart materials, which we will discuss it little later. It has some actuators, which are called smart actuators. We will again discuss this little later and it also has a controlled mechanism to actually integrate this function.

In order the system to be smart it requires some external stimulus and this external stimulus is given by either a strain or it could be a light, it could be an electric field, a magnetic field, a temperature, a pressure whatever it be it requires a stimulus and when the stimulus is given to the structure or a system it has to respond in a manner that we desire in order to make it smart and the response could be a motion or maybe change in the optical properties or change in the modulus, you want to change the material, you want to change the surface tension, you want to change the pyroelectricity property whatever it be about the structure.

So basically a smart system has to have these 3 features, integration of functions, stimulus and response. Hence we can basically define the concept definition of a smart system as a smart system can be described as a system, which has an intrinsic sensor, actuator and a control system whereby it is capable of sensing a stimulus, responding to the stimulus and revert into the original state after the stimulus is removed.

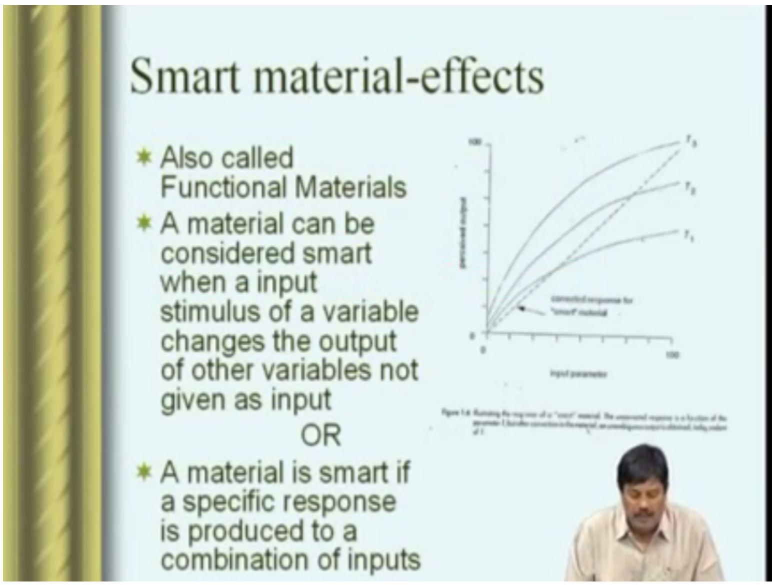
(Refer Slide Time: 07:16)



So the basic fundamental component of a smart system is essentially smart material. So how do we define the smart material? A smart material essentially is a material, which has an intrinsic or extrinsic capabilities to respond to an external stimulus in a functionally useful manner. So basically for example we may have a zinc oxide varistors, which are normally used as a protection against a high voltage breakdown in power lines.

When these power lines are struck by a lightening obviously there is an enormous increase in voltage. So at that point of time, this varistors will make the electrical resistance decrease and these resistances are passed on to the ground and prevent a massive catastrophic failure. So basically here zinc oxide varistors acts like a smart material and basically helps us to actually remove the ill effects of heavy voltage due to lightning strike.

(Refer Slide Time: 08:39)

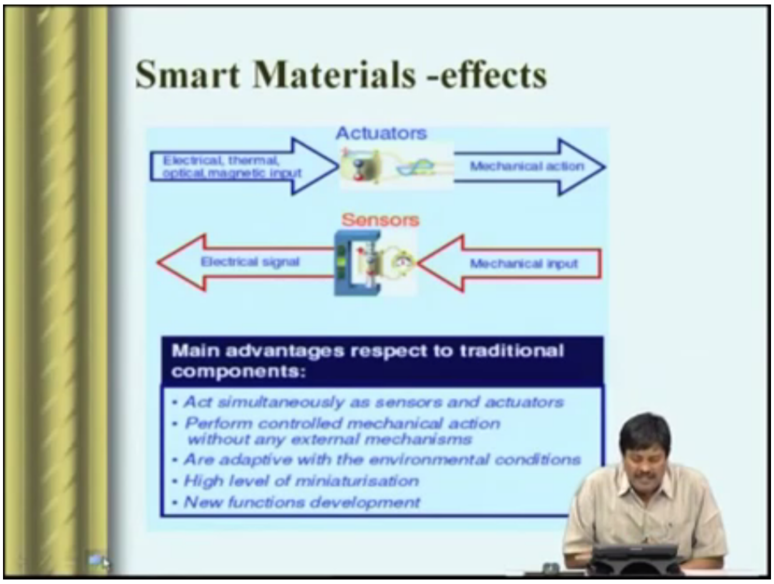


So what are the smart material effects? So the smart materials are normally called the functional materials. Why it is called functional materials? It is basically because this material when an input stimulus of a variable is given, it changes the output that are not given as input. So in order to understand this let us consider this graph where there is it is plotted with respect to the input as well as the output.

And suppose this input or the output depends upon a particular parameter T whose variation is nonlinear and for each values of T, T1, T2, T3, you basically get a different input output variation and now if we desire that these nonlinear variation is not what we want and we want a variable that is linear we can basically tune this parameter T3 on which on the parameter T on which either the input or output is depending in order to make it linear.

So this is in effect is done by the smart material or in other words smart material or a material is considered smart if a specific response is produced to a combination of inputs and here the combination of inputs is T1, T2, T3 etc.

(Refer Slide Time: 10:32)

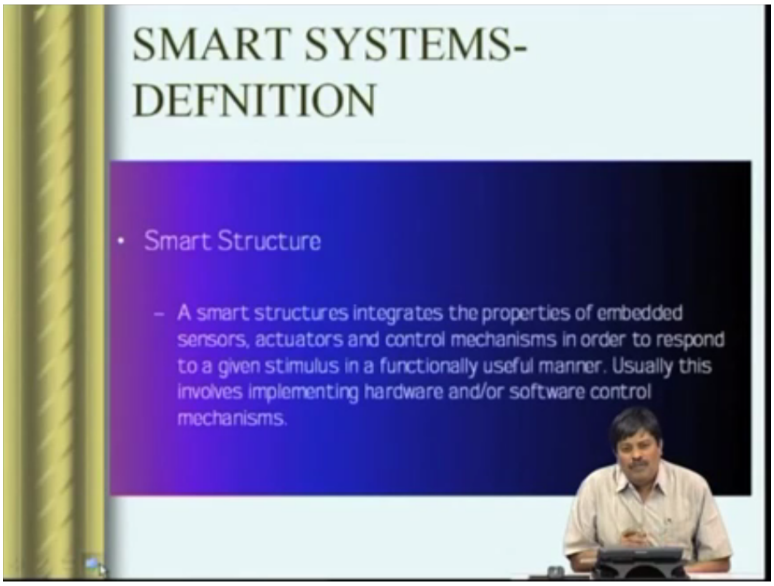


So what are the smart material effects? There are 2 different effects. The smart materials can act like a sensor; it can act like an actuator. If it is acting like a sensor, when input is given say suppose we are talking about a piezoelectric materials as a sensor, which will cover at the later part of this lecture. Whenever we give a mechanical input, we get an electrical signal output and that is basically a sensor action, which is called the direct effect.

On the other hand, if you give an electrical input and we get a mechanical force effect then it is called actuation. So we need some force to actuate. We need any other signal like electrical or a voltage signal to actually sense it. So any smart material will have 2 effects, which is called the direct effects, which is called the sensing effect and the converse effect, which is called the actuator effect.

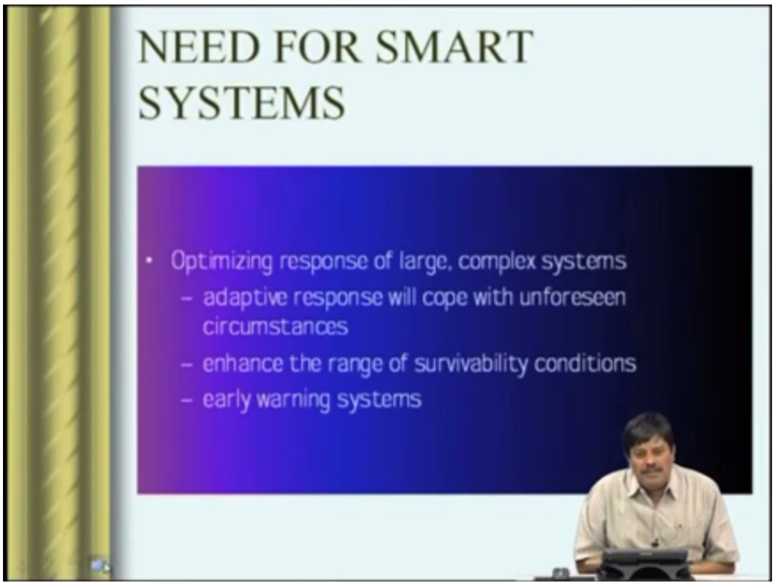
So the main advantage of this smart material over traditional materials are you can use it for both sensing and actuation. It can perform control mechanical action without any external mechanism. It can be adaptive. It can change itself to the environmental condition and it has potential for high level miniaturization, which is today is what we looking at the smart systems and many new functions can be actually developed using these materials.

(Refer Slide Time: 12:12)



So now let us come to the definition of a smart system. So taking into account what we said now is smart system basically integrates the properties of an embedded sensor, actuators and the control mechanism in order to respond to a given stimulus in a functionally useful manner. I insist here the functionally useful manner. This is the manner in which we want the system to behave. Usually this involves implementing both hardware as well as the software control mechanisms.

(Refer Slide Time: 12:52)



Next, we need to address why do we need the smart system? So there are various reasons that you can find why we need the smart system, but here are a few. Normally, many systems are susceptible to unforeseen circumstances such as in a mechanical structure you have heavy vibrations, in electrical structure there is a heavy rise in voltage. So we need the system to be adaptive so that such harsh environment does not lead to the destruction of the smart system.

So the adaptive response of the structure can be achieved by the use of smart systems. In addition, it can increase the range of survivability conditions. Basically, it can increase the life of a structure because when it reduces vibration and many early warning system for example if the vibration levels in a structure is very high, we can actually design a sensor which can give us the early warning about the presence of excessive vibrations.

So early warning systems can be developed, the structures can adapt itself for unforeseen circumstances, harsh environment etc.

(Refer Slide Time: 14:20)

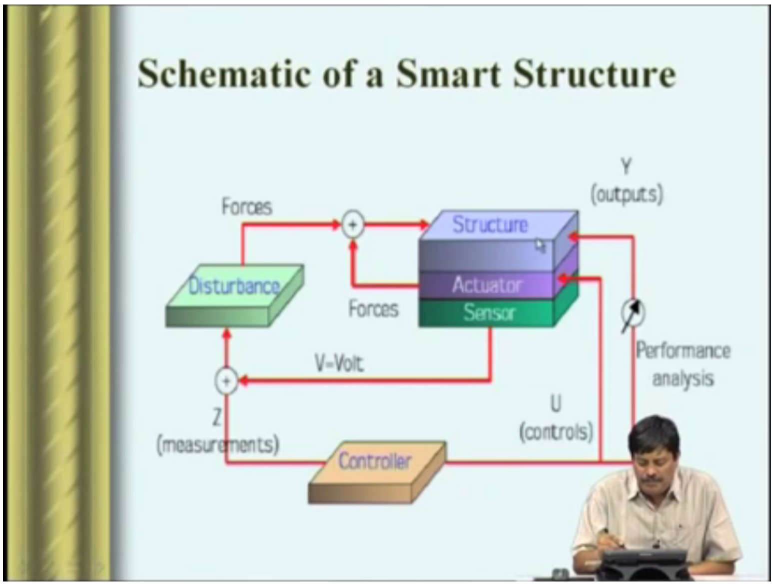
The next need is basically for performance enhancement. For example, we take an example of antenna and the success of the antenna or the behavior of the antenna is actually decided by how accurate it points and the pointing of the antenna to the required position is one of the key aspects in the behavior of the antenna. This can be precisely achieved by smart systems. It can precisely position the antenna in the point the antenna to the required accuracy. So this performance enhancement is another important advantage of using a smart system.

(Refer Slide Time: 15:08)

The third important need is the functionality. We are talking about functionality means today we have structures which is stringent, design requirements where it has to be light weight. So that means we need to have an optimized structure. If the optimized structure is there then the structural integrity of the structure is in big question because of the light weight. So again we go back to the previous performance enhancement whenever we have a smart system, which can actually has early warning system of impending we can take corrective action that means we can basically design the structure which are light weight.

We can also have the smart system perform preventive maintenance through early warning system and which can also do performance optimization. So the functionality is one big aspect of having the smart systems.

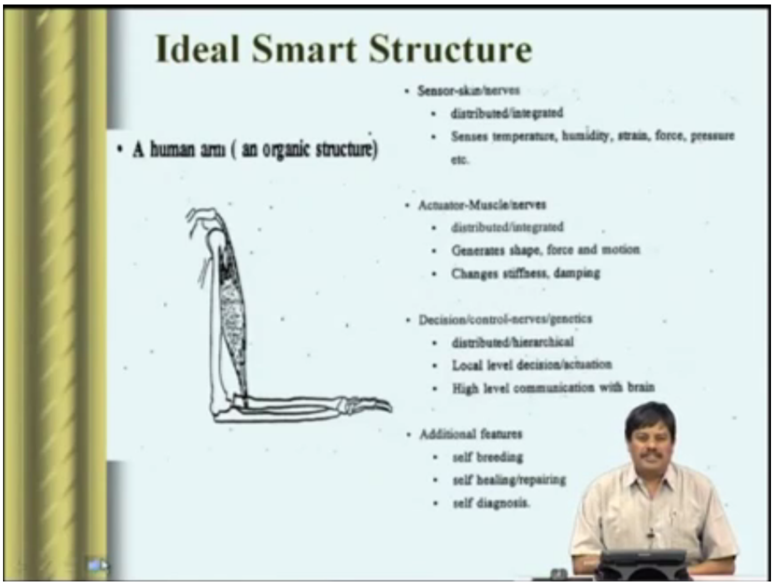
(Refer Slide Time: 16:10)



Next we will go and find out what is a schematic of the smart structure? So basically a smart system or a structure would have a structure, it has a structure. The structure has actuator, a sensor. So basically whenever there is a disturbance that is given to the structure, it can be like a force. If it is a piece of sensor, then the sensor will measure the strains in the structure and give out in the form of a voltage.

And if the voltage levels are very high indicating there is a high level of forces are there, then there is a control system, which triggers the actuator to give a counteractive force so that the present vibration levels in the structure can be minimized through this external force. So a schematic is basically a sensor will give out a signal and the control circle will decide whether to trigger the actuator or not if it has to do then necessary action to control this ill effects of this high levels of input that is coming to the structure.

(Refer Slide Time: 17:34)



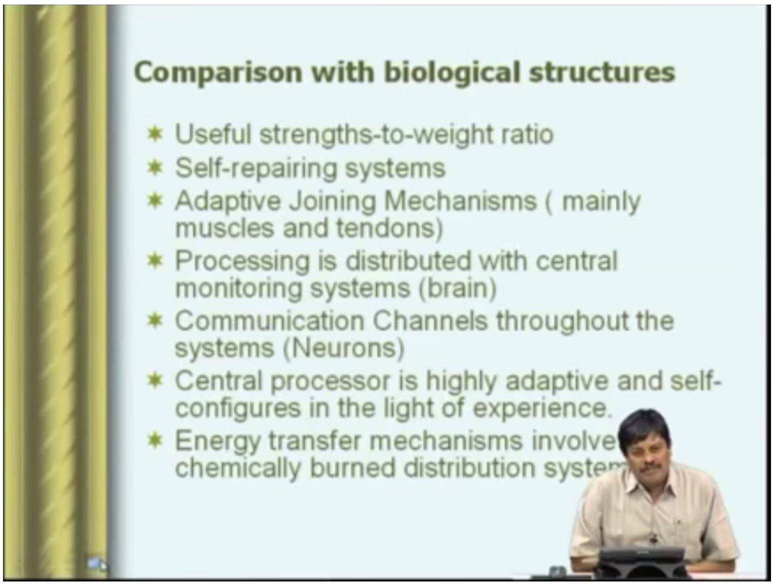
Next we will see what is an ideal smart structure? Our human body is essentially an ideal smart structure. So let us take a small human arm, which is an organic structure and look at what are the constituents of it and how we can relate it to our smart system. The human arm basically has nerves or a skin, which acts like a sensor and these sensors I call it are distributed and integrated and what all it can sense?

It can sense a number of things like temperature, humidity, strain, force, pressure etc. The arm has muscles on nerves, which acts like an actuator. Again here, the actuator is distributed and integrated and it generates the shape, force and motion that is needed to the circumstances and it can change the stiffness and damping levels. So our muscle becomes a true actuator.

And the decision on the control system which we have in the smart structure is essentially controlled by brain having high level of hierarchical and distributed decision making process, local level decision can be made by actuation and the high level of communications is done through neurons. In addition to above, there are additional features that our human body has they are self-breeding, self-healing, and self-repairing, self-diagnosis. These are some of the things.

So our body is a truly intelligent structure that is why we call and to implement the additional features is a tall order in these systems.

(Refer Slide Time: 19:39)

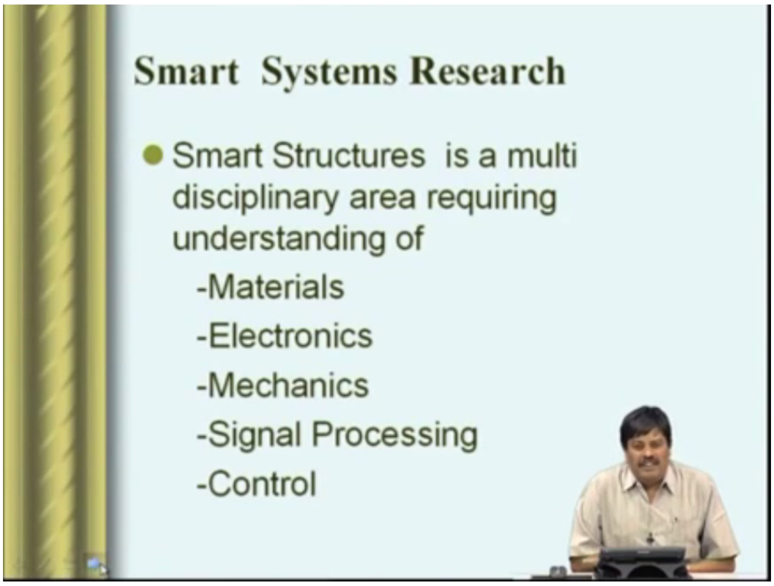


So let us compare our smart system with the biological structure. If you look at the biological structures, they have a very useful strengths-to-weight ratio. As I said earlier, they are self-repairing and adaptive joining mechanism. Suppose there is a fracture, it joins by itself after sometime, which is possible mainly by muscles and tendons and the process is highly distributed the processing of information with the central monitoring system that is the brain which acts as the main part, which actually involves in the decision making process.

And the communication of instruction from brain is given to other parts of the structure through neurons, which is really high speed communication and the central processor is highly adaptive and self-configures in the light of experience and whatever we eat it is converted into energy and the energy transfer mechanisms involves chemically burned distribution systems.

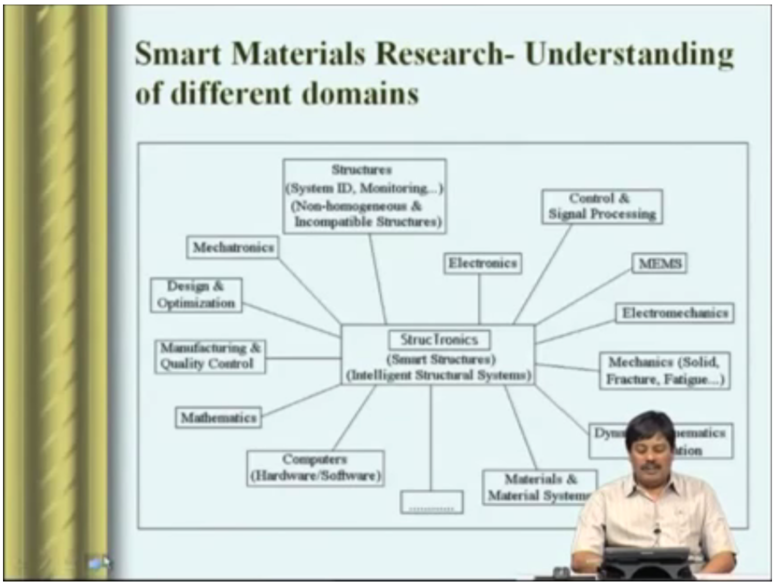
So as I said earlier our human body is a really intelligent structures and the aim here is to basically incorporate all those behavioral aspects or the smart aspects of the human body into the system.

(Refer Slide Time: 21:07)



So now coming back to the smart material research. Basically, smart structures is a multidisciplinary entity requiring understanding of materials, electronics, mechanics, signal processing and control.

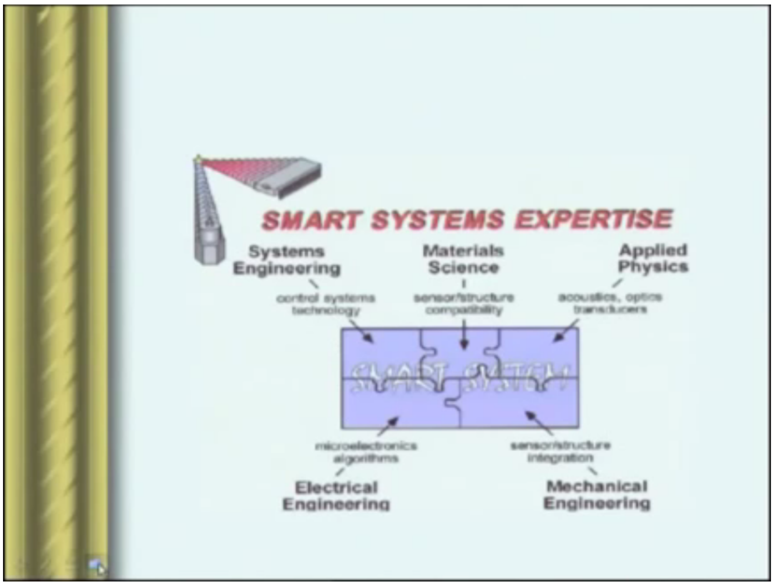
(Refer Slide Time: 21:26)



So this view graph basically tells what are the domains of knowledge one requires in order to understand the smart material systems. We require the understanding of mechanics and structures, the control and processing, MEMS of course microsystem, the MEMS is important aspect of it, electromechanics, then dynamics and vibrations, materials and material systems, computer hardware and software, mathematics, manufacturing and quality control, design optimization, mechatronics.

All these things put together requires a broad area of understanding of science and engineering.

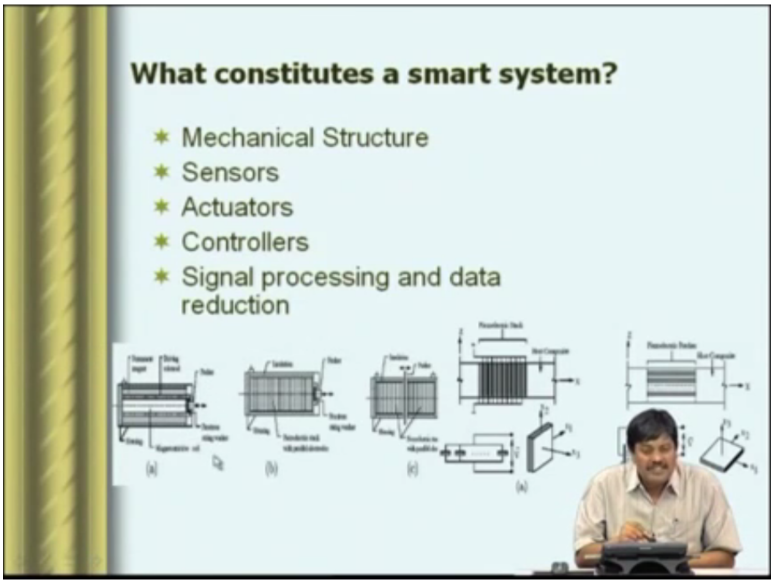
(Refer Slide Time: 22:17)



So we can think about smart system as a big jigsaw puzzle requiring understanding of systems engineering as I said where the control system comes into big picture. So in this view I have splitted in terms of specific disciplines here and what area we need here. In the area of system engineering, we need the understanding of the control system. In the area of material science, we need to come up with new materials for sensors, actuators.

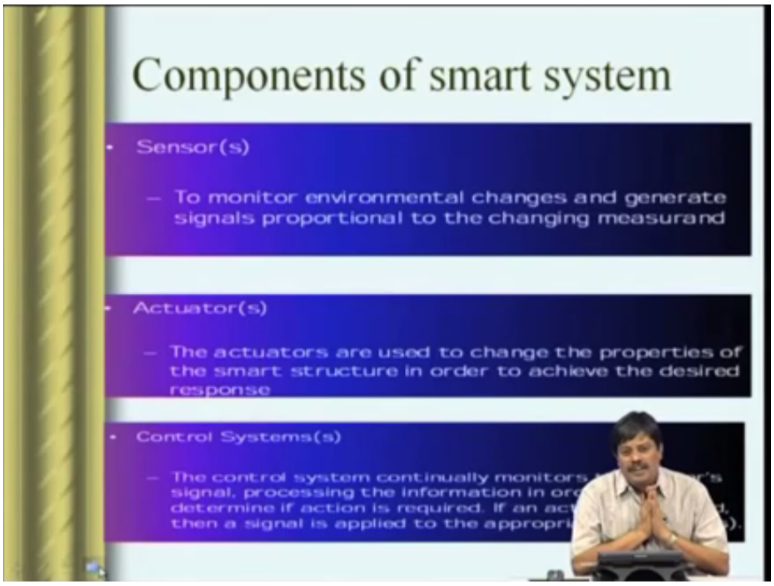
In the area of applied physics, we need to understand acoustics, optics, transducers. In the area of electronics and electrical engineering, we need to understand microelectronics because for the microsystems and in the mechanical engineering, we need to understand sensor and sensor integration. So it is basically can be a thought of a big jigsaw puzzle putting together without clear demarcations. There maybe overlap between many areas of engineering and science.

(Refer Slide Time: 23:15)



So in summary we can say that a smart system constitutes mechanical structures, sensors, actuators, control, signal processing and data reduction. So here are a few smart sensors and actuators that are been shown here.

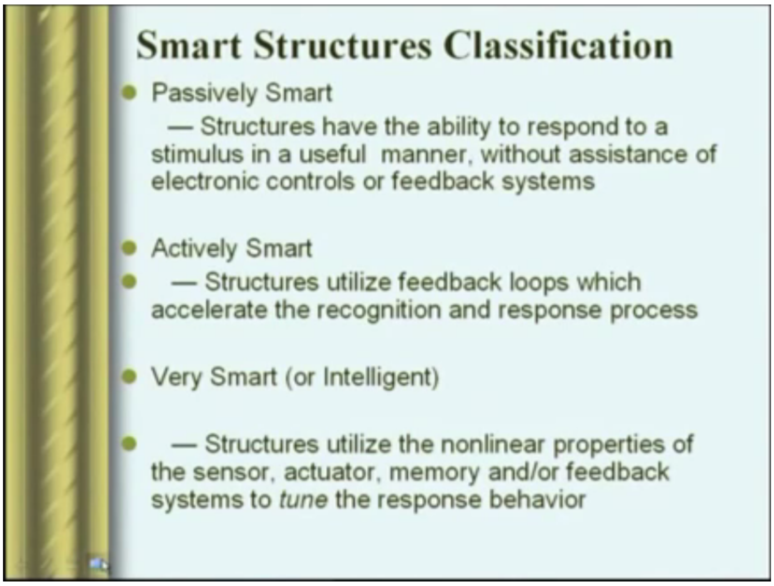
(Refer Slide Time: 23:34)



So let us understand what are the functions of each of this? What they do in a smart system? Let us talk about the first component that is a sensor. The basic function of sensor is to monitor the environmental changes and generate signals proportional to the changing measuring parameter. We call it as a measure end. The measuring parameter could be an electrical signal, a temperature, optical properties or whatever it could be.

Similarly, the actuator is basically the main functions are used to change the properties of the smart structure or the smart system in order to achieve the desired response. Suppose we want the vibration of a structure to be reduced we basically actuate through smart material force in order to reduce it. So basically actuator has to perform the actions that are desired for a desire response and of course the control system is basically control system monitors the sensors output continuously and then takes an appropriate action to trigger the actuator as and when it is needed so that is the main responsibility of the control system.

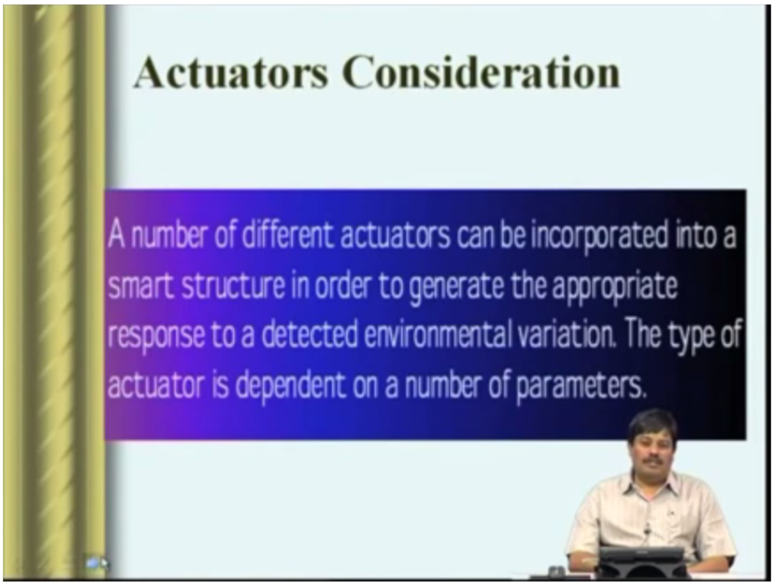
(Refer Slide Time: 24:59)



Smart structures classification, there are number of ways that you could basically classify the smart structure. They can be passively smart that means basically the actuation or the response the structure has to do without any electronic control. So this is called passively smart. One example is the fiber optic sensors, which we will come and discuss it later.

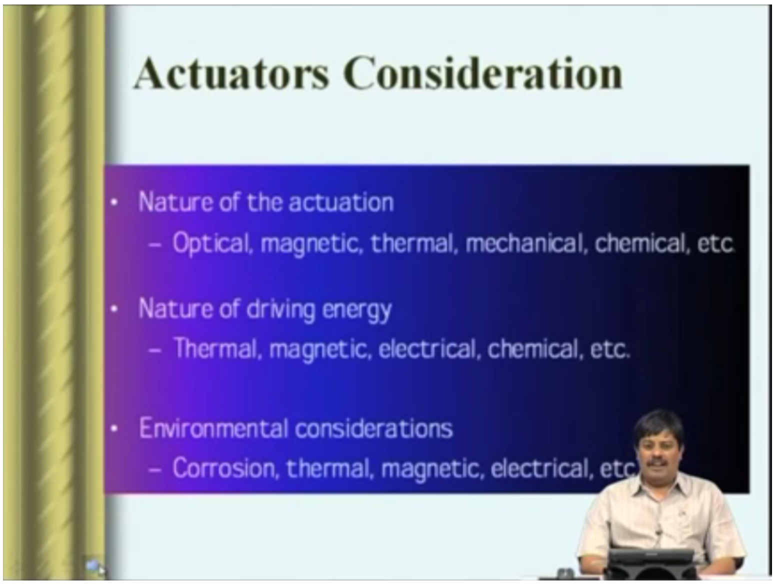
The second way of classifying is when the structure is actively smart, which more structures are where they use electronic control, feedback loops in order to actually get the desired response. And the very smart structures are basically they utilize the nonlinear properties of the sensor, actuator, memory and feedback system to tune the response behavior, but most of the structures what we come across today or more recently is the structures of either passively smart or actively smart.

(Refer Slide Time: 26:11)



So there are a number of considerations that you need to take care while choosing actuator or while choosing a sensor for a particular smart system. A number of different actuators can be incorporated into a structure in order to generate the appropriate response to a detected environmental variation from the sensor and the type of actuator that you want to use depends on host number of factors, which are listed below.

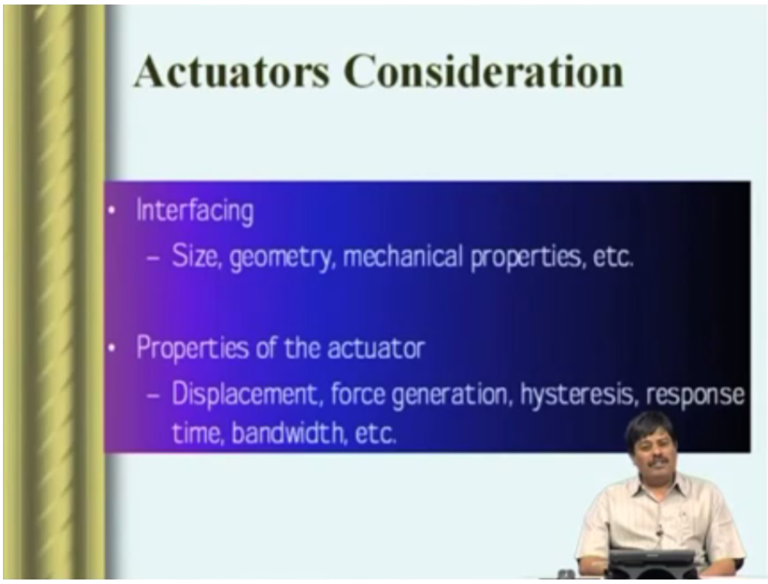
(Refer Slide Time: 26:41)



The first factor that you need to consider is the nature of actuation, is the actuation optical, is the actuation magnetic. For example, magnetostrictive material can give an actuation that is magnetic if it is thermal or mechanical etc. So the nature of actuation will decide upon the type of actuator that you need and the nature of driving energy is the actuator driven by thermal energy, magnetic energy, electrical energy etc.

And the other aspect that are to be considered when you place these actuators on to a smart system, the environmental conditions such as whether it reacts to the corrosive environment, thermal environment, magnetic environment or electrical environment is something that one has to consider before you choose an actuator.

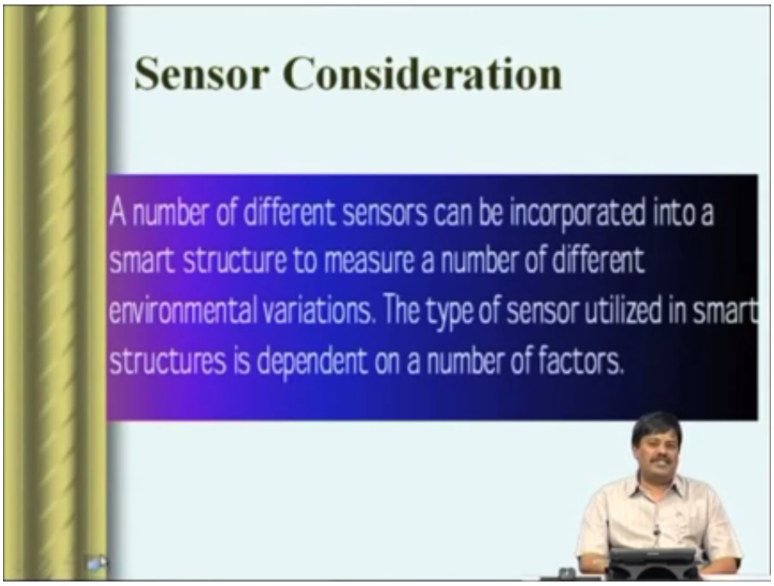
(Refer Slide Time: 27:39)



The other aspect that you need to consider for actuation is the interfacing whether the size is going to fit within the system, geometry that is going to be accommodated within the system, mechanical properties are okay to get the necessary actuation force etc. The other important aspect that you need to consider while choosing an actuator is the properties of the actuator. What is the displacement or the stroke length that it can generate?

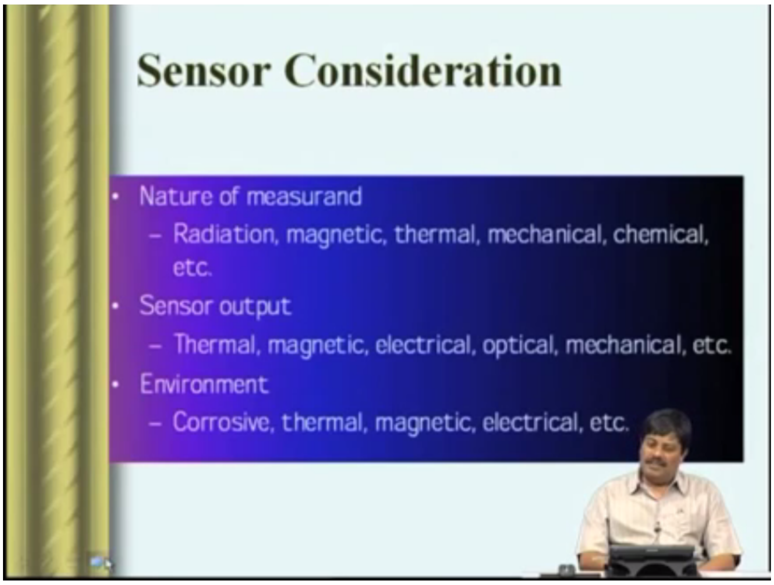
What is the force in turn it can generate these actuators in order to do the required functions? What are the hysteresis whether the loss is there? If the loss is there, the force will be less. The response time is it fast, slow, band width etc.

(Refer Slide Time: 28:29)



Similar to actuators we can also have a number of considerations for sensors and the number of sensors can be incorporated depends upon a host of other factors as in the case of actuators.

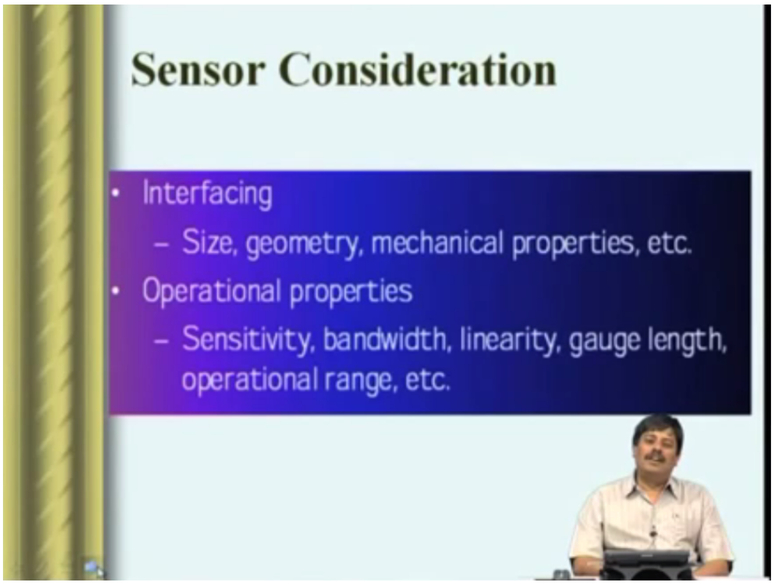
(Refer Slide Time: 28:49)



Some of the factors are nature of the parameter you are measuring, we call it as measure end whether it is a radiation, it is an electric field, magnetic field, thermal field, chemical field etc. So depending upon the measure end you can choose the sensor. For example, if you are looking at the optical properties, you need to choose fiber optics. Next is the sensor output, whether the output is going to be thermal, magnetic, electrical.

For example, if it is a piezoelectric material you get an electrical signal in forms of voltage and this voltage has to be related to the basic force if it is put on a mechanical structure. So that is something that we need to understand and of course as in the case of actuator we need to look at the environmental condition whether the sensors can resist corrosive atmosphere, thermal atmosphere, highly magnetic field intensive environment etc.

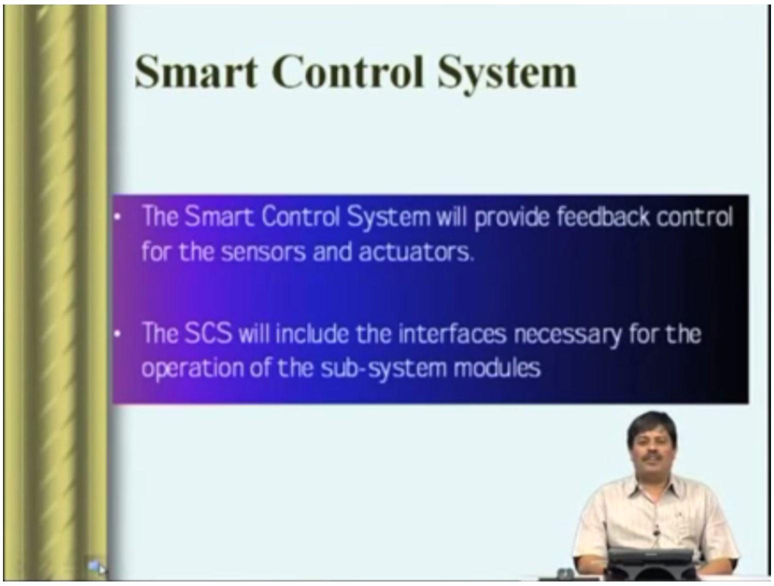
(Refer Slide Time: 29:50)



So these are some of the sensor consideration. In addition to that, we have interfacing as in the case of actuators and the operational properties these are very important for the sensors, how sensitive it is, for example if you are dealing with the electrical measurements or a capacitor measurement, if it is of the order of pico farad or micro farad. Those are very important whether you have ability to measure such small changes.

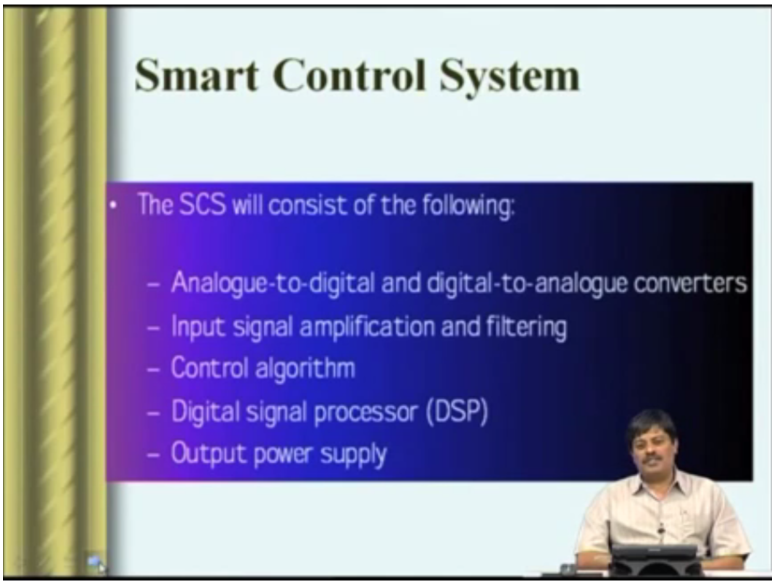
So the sensitivity depends upon how small the changes in the properties of the sensor that gives out is effective, how well we can actually measure it. These are some of the important consideration for the sensor.

(Refer Slide Time: 30:38)



Coming to the smart control system basically will provide a feedback control for the sensors, for the actuators, so the control system will have the necessary interfaces to the subsystem modules.

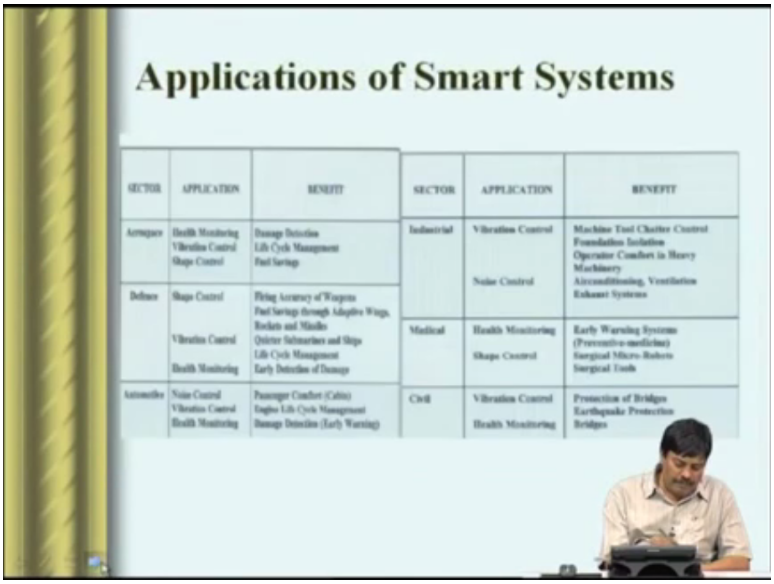
(Refer Slide Time: 30:55)



And it will consist of a number of things among them or the analogue-to-digital and digital-to-analogue converters, input signal amplification and filtering. Suppose the response obtained is highly noisy, we need to have a filter in place, control algorithm and that depends upon what type of structure, what kind of actuators, what kind of sensor input you are getting.

For example, if it is a PZT type actuators basically the control system has to generate enormous amount of force in order to control the mechanical effects put on a structure. And the control algorithm depends upon the sensing input and what kind of output that the sensor has to give to the actuator. We also need a digital signal processor to process the signals and the output power supply. These are the important components of the smart control system.

(Refer Slide Time: 31:49)



Now let us look at the range of applications that smart system has. I am going to come back on the applications in lecture number 6, but before that we need to see where all we can use smart systems or what is the range of applications that we have? Let us look at the sector by sector applications. In aerospace, we have the use of smart system in monitoring the health of the structure, to control the vibration, shape control.

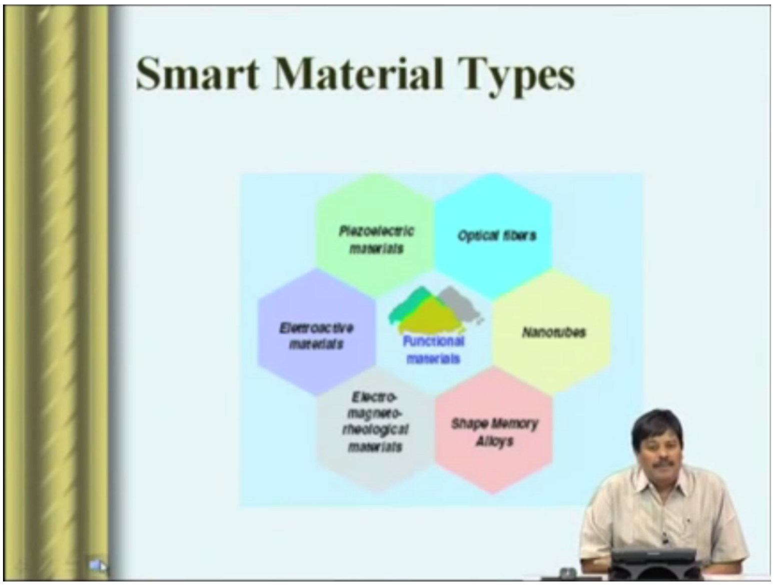
These basically will be used to actually detect damages, to find out the remaining life on the structure and also for fuel saving, a huge benefit if you have the system. In the area of defense, we need to have this for shape control, vibration control and health monitoring. In addition to above, we also have quieter submarines, quieter rockets, fuel savings and many other advantages.

In automotive, the major emphasize on smart system is for noise control, vibration control and also health monitoring where the major benefit is passenger comfort, engine lifecycle management and also damage detection that is the early warning system. In the industrial engineering sector, we can use it for vibration and noise control. If the major advantage is the machine tools are quieter without any chatter, foundation, vibration, isolation, operator comfort in heavy machinery, air conditioning and ventilation etc.

In medical, we have it for health monitoring and also shape control, early warning systems like preventive medicines some of the disease diagnostic kits are also a part of this medical. Then in the civil engineering, vibration and health monitoring where we have many bridges, which are very old, we can assess the state of the current structure and take remedial action to avoid any catastrophe.

So we see that there is whole range of applications of smart systems in all branches of science and engineering.

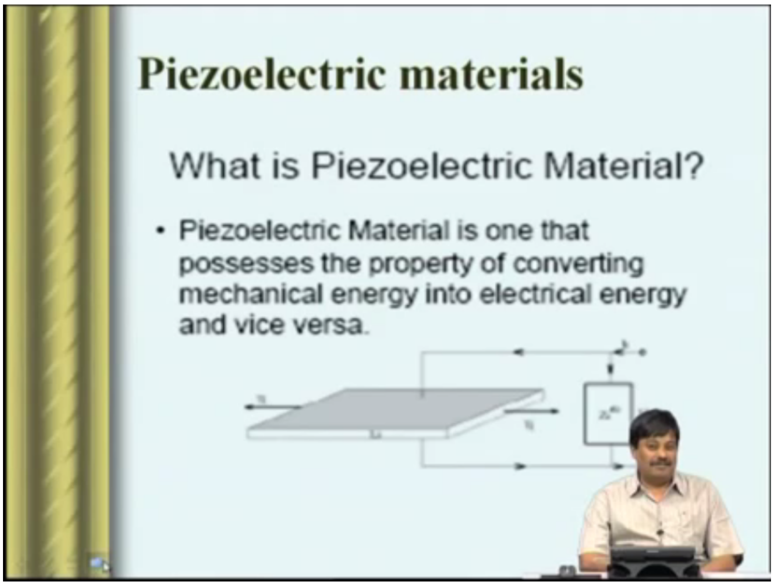
(Refer Slide Time: 34:13)



Now let us come for the next 20 minutes on what are the different smart material types. As we said earlier, smart material is a fundamental component of either a smart sensor or an actuator. There are a number of materials that have that basically behaves like a smart material. The most common type of materials are the piezoelectric materials, the optical fibers, the shape memory alloys, the electroactive materials, electro and magneto rheological fluids and even more recently carbon nanotubes.

So in this lecture, I am not going to talk about all this, but I am going to talk about some of the behavioral of some of these materials.

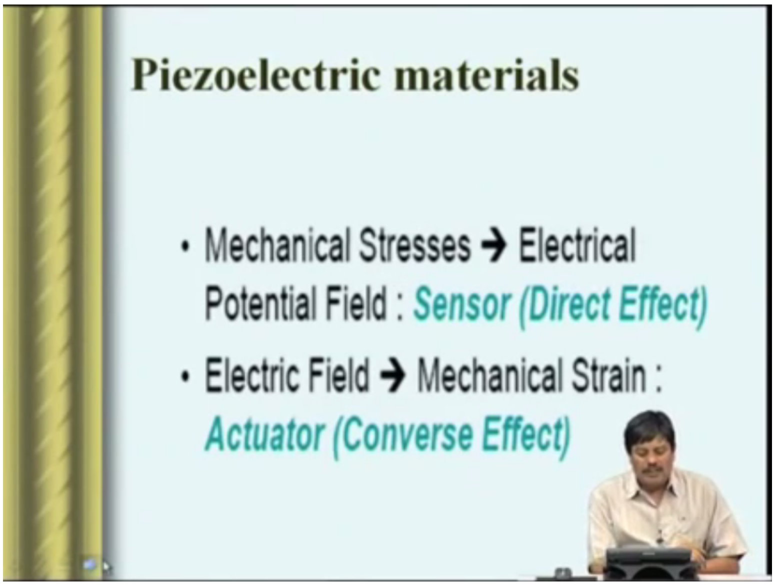
(Refer Slide Time: 35:02)



Let us begin with the piezoelectric material. What is a piezoelectric material? So piezoelectric material is the one that converts the mechanical energy into electrical and vice versa. So basically here there is a diagram. There is a structure with the piezoelectric film there, which is pulled here. So when you apply a voltage, it generates a strain and when you induce a strain through a force, it generates a voltage.

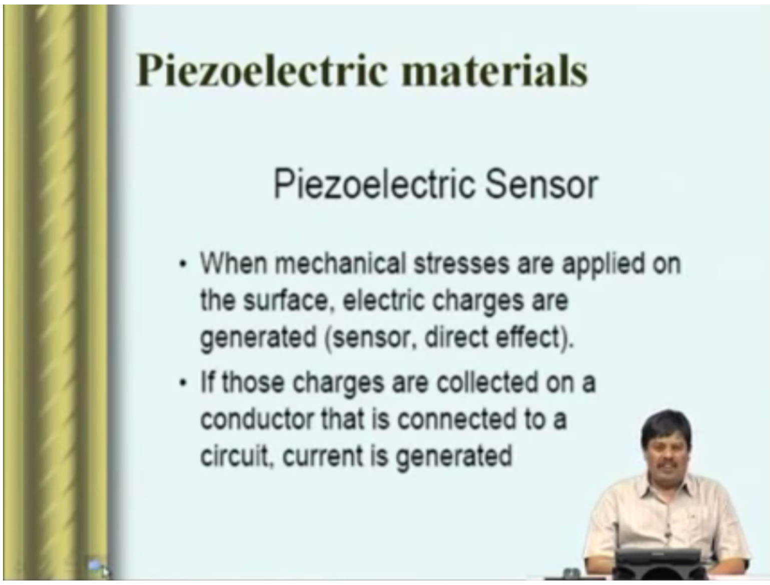
So basically mechanical energy is converted into electrical and electrical into mechanical.

(Refer Slide Time: 35:40)



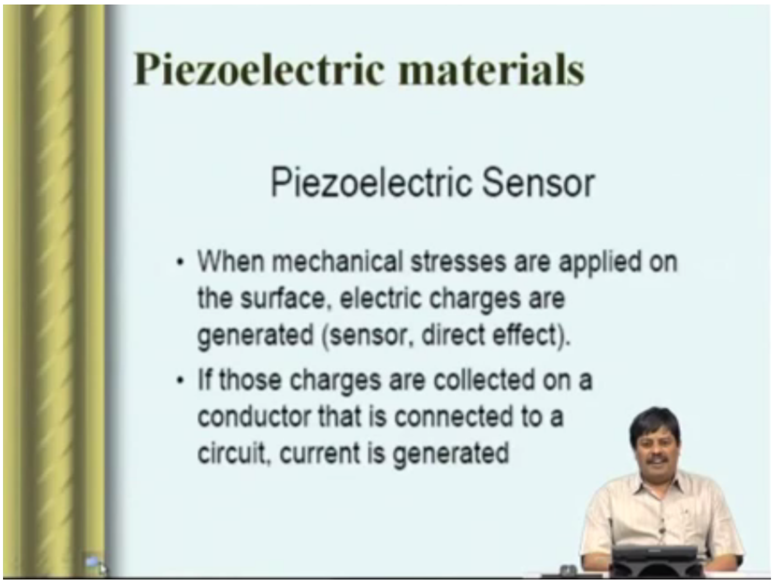
So this is what is given here. So the mechanical stress are generated, the mechanical stress inputted into the system generates an electrical field, which is called the sensor effect as I said earlier it is called the direct effect and whenever you feed an electric field and it generates a mechanical strain, which is called the actuator effects. So for sensor we use this equation and for actuator we use this equation.

(Refer Slide Time: 36:12)



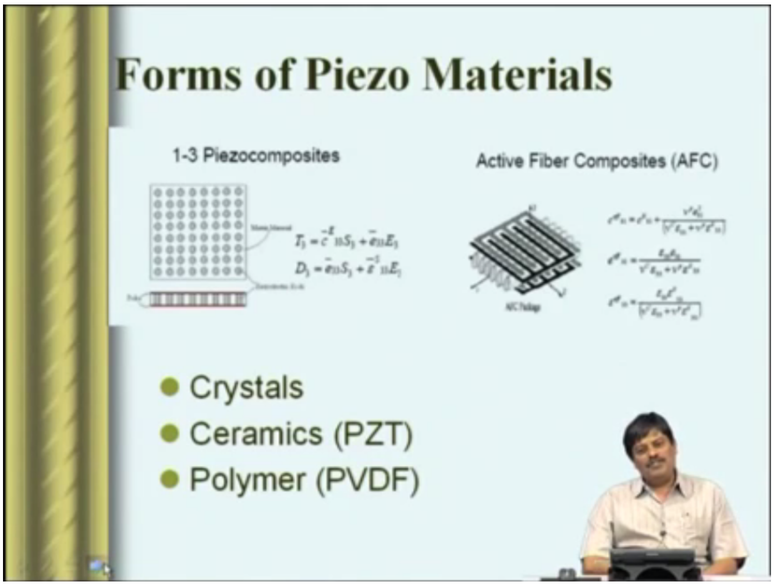
So as I said earlier in a piezoelectric sensor, when a mechanical stresses are applied on the surface, the electrical charges are generated because of this sensing effect and these charges are collected on a conductor and that is connected to a circuit and a current is generated. The current gives out a voltage signal, which actually states the state of this particular structure.

(Refer Slide Time: 36:44)



But if I want to do the inverse effect that is when I want to use a piezoelectric material as an actuator here when an electric potential or a voltage is applied to the surface of the piezoelectric material, the mechanical strains are generated and if the piezoelectric material is bonded on to the surface, these strains are applied to the structure and the forces are generated to actually move the structure the way we want. So basically it is doing an actuator operation.

(Refer Slide Time: 37:21)



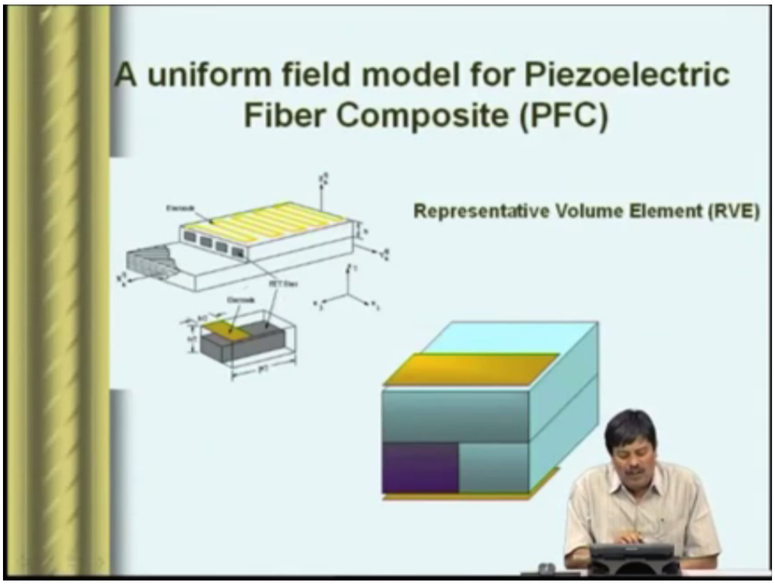
There are number of forms of piezos, some forms of piezos can be used only as a sensor and some other can be used only as an actuator and some can be used for both sensing and actuators. The piezoelectric materials are available in crystal form and ceramic form and the ceramic form is essentially PZT, it is called lead zirconate titanate. Basically, it is a actuator material having enormous actuator authority.

We say that if the ability to generate large force, we call such a material as enormous actuation authority and the PZT material has significant actuation authority so it is mostly used as an actuator. The other material is the PVDF, it is called polyvinyl difluoride material. It is the polymer form of the piezo material, which is used only as sensing. It cannot perform actuation effectively.

It is mostly used as a very good sensing material. In addition, you can have a piezo composites where the piezo material are embedded in a matrix like system or we can also have an active fiber composites where in the form of a laminated composites you basically embed them, electrode them and make it multifunctional. The basic constitutive law, the direct and the converse law is given here.

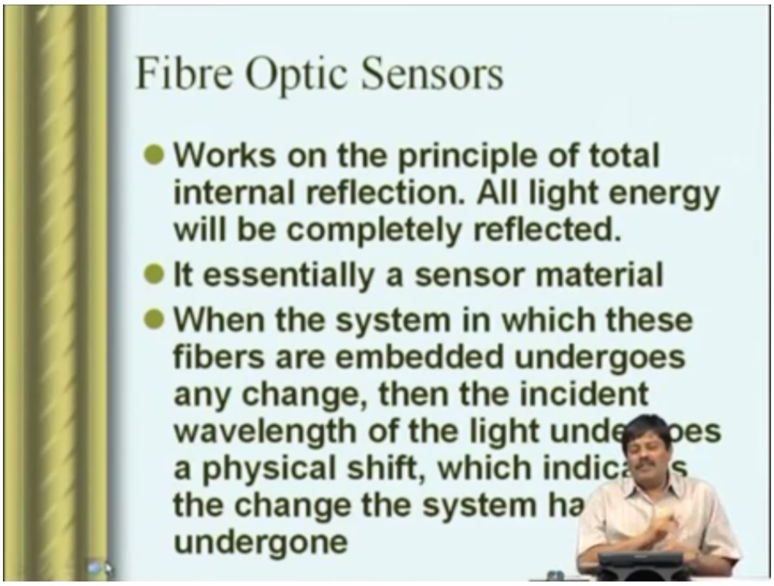
So the basic constitutive law is given by this. It basically states the strain is proportional to stress and also the electric field. Here e3 is the electric field and the electrical displacement is directly proportional to the strain. So this e33 parameter is basically the one that provides the coupling between the electric field and the mechanical stresses and this is this component e33 if it is very high, we call it as highly sensitive. This is what is required in most of the piezo materials.

(Refer Slide Time: 40:02)



The other form that we have is the piezo fiber composite as I said earlier laminated composites is used extensively as a structural materials for aerospace because it is variable light weight where there are fibers. Now if you replace these fibers by the TZT fibers or the piezo fibers and electrode it and it can be used basically as an actuator to control it becomes a piezo fiber composite, it can do multiple operations in addition to taking load it can actuate to actually reduce the vibration levels, noise levels, etc.

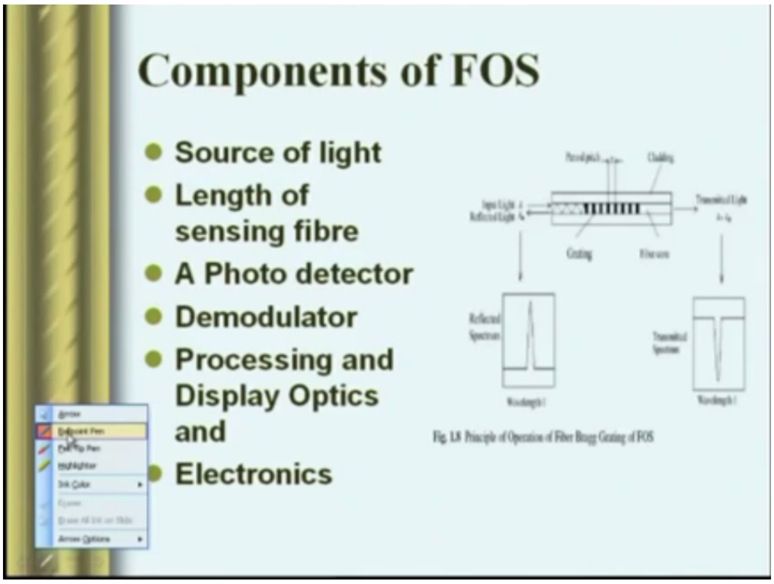
(Refer Slide Time: 40:38)



Next, we will go to the fiber optic sensing. Here the fiber optic sensor is basically works on the principle of total internal reflection. In the total internal reflection, all the light energy is reflected without any reflections. It is basically a sensor material, fiber optics cannot do any actuation. So how does it work? When the system in which these fibers are embedded undergoes any change then the incident light has a wavelength and that changes when it comes out.

Monitoring the wavelengths of the incident and also the reflected spectrum we can actually say something is going on in this system and hence it can be used as a sensor. In fact, this is the first sensor that came out as early as 1981 when it was actually used to monitor the temperature for fabricating the composite structure.

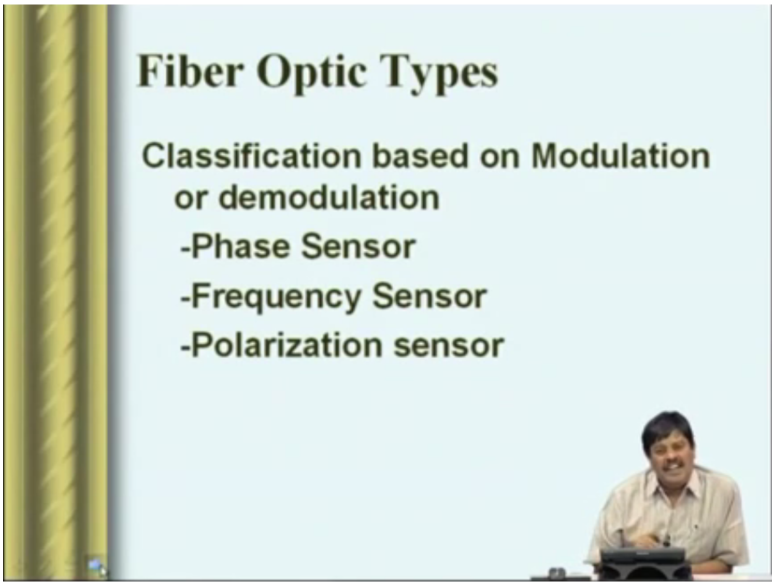
(Refer Slide Time: 41:42)



So basically this is shown here in this diagram. There is an incident light that is coming here and when it falls on to this optical fiber, which is grated we call it as fiber Bragg grating sensor, it gets reflected and some get transmitted and you can see the spectrum looks like this and this is the wavelength. If the change in the wavelength basically says there is something going on in the structure and this wavelength is a function of the stress that is undergoing on the structure where it is embedded.

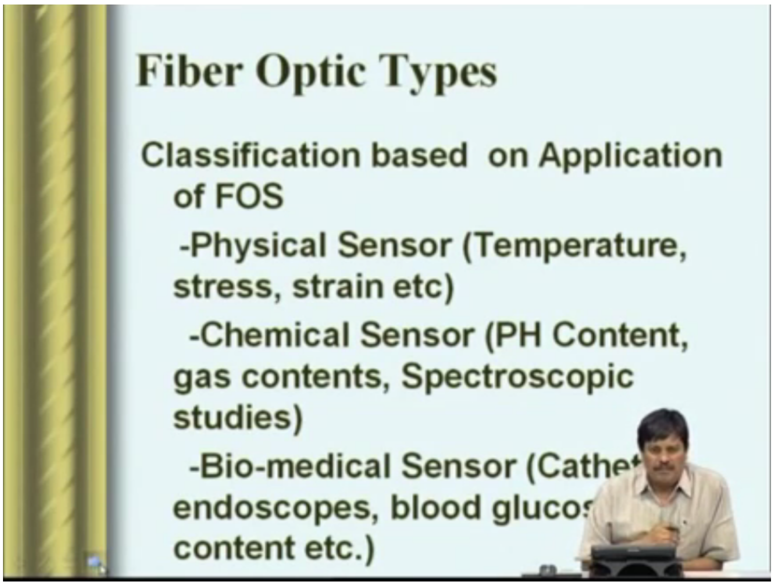
So this is the principle of operation of the fiber optic sensor. So the components of the fiber optic sensors are the sources of light, the length of the sensing, the photo detector, demodulator, the processing and display optics and electronics. These form the components of the fiber optic systems.

(Refer Slide Time: 42:56)



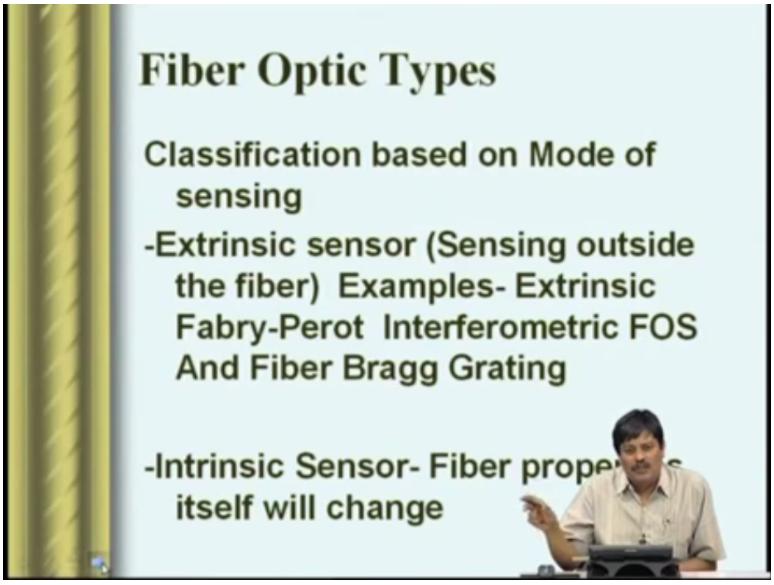
So there are many ways that you can use the fiber optics, it can be sued for sensing many things like temperature, pressure, gases, strains etc. Depending upon the functionality of the sensor it can be classified into a number of different waves. The first classification is based on the modulation and demodulation where if it is used to measure the phase it is called the phase sensor, frequency it is called frequency sensory, polarization is called the polarization sensor.

(Refer Slide Time: 43:29)



It can also be classified on the applications. Basically, if it is a physical sensor, it can measure the temperature, strain and stress etc. If it is a chemical sensor, it can measure the pH content, gas content, etc. If it is a biomedical sensor, it can be basically used to sense the parameters for catheters, endoscopes, blood glucose etc.

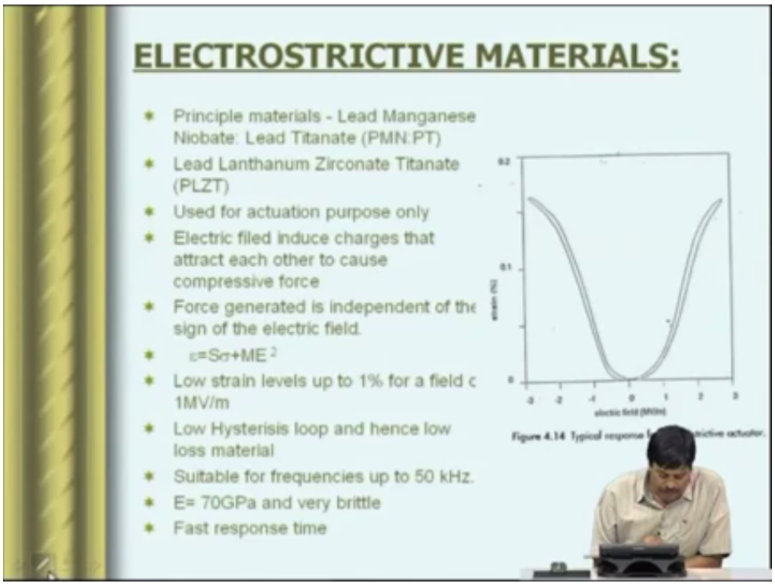
(Refer Slide Time: 43:52)



Fiber optic sensors can also be classified on the mode of sensing. There is extrinsic sensor, basically sensing outside the fiber. So nothing happens to the fiber. Based on certain things happening within this fiber sensor, you could see the response outside this fiber that is called the extrinsic sensor and most of the sensors which we normally used in smart systems are extrinsic sensors.

Some of the examples are the Fabry-Perot Interferometric sensors, which is called EPEFPI sensor and the fiber Bragg grating sensor, which I talked about little before. These 2 types of sensors are the extrinsic sensors. The intrinsic sensors are those where the fiber property itself change because of certain inputs and these are called intrinsic sensors. These are not very, very common in the use of smart systems.

(Refer Slide Time: 44:49)

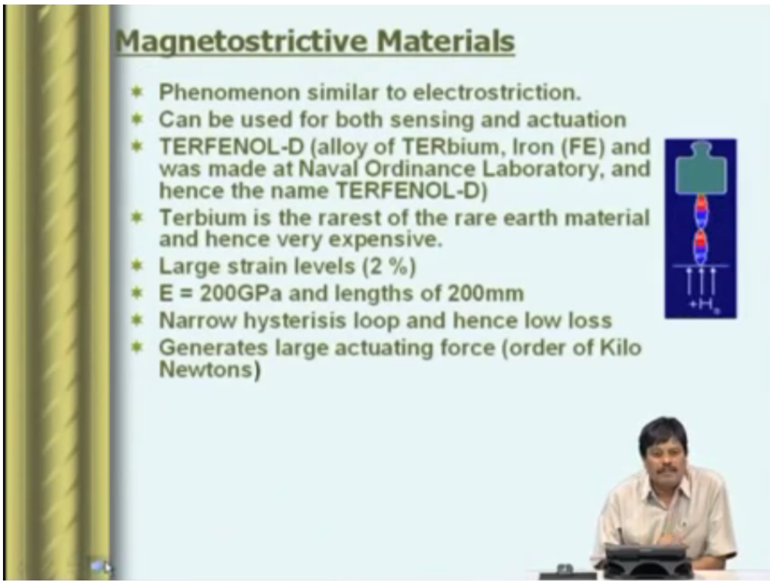


The next material we will talk about is the electrostrictive material. This is very similar to the piezoelectric material where we have this quantity strain as oppose to PZT the strain is quadratic in electric field that means in the absence of mechanical stress you can never get a negative strain here. So we need to use a bias voltage for actually measuring this strain. There are 2 different types of electrostrictive materials.

One made from lead manganese niobate, lead titanate, which we call it as PMN-PT electrostrictive materials and other made from lead lanthanum zirconate titanate, which we call it as PLZT sensor materials. So they are basically used only for actuation purpose. There is nothing reported in the literature about using this material for sensing. So basically for a given electric field, it generates square of the electric field, the strain will be square of the electric field basically.

The main advantage of this is it has an extremely fast response time, it can work up to 50 kilohertz of frequencies, has a material property as much as aluminium with 70 GPa, but it is quite very brittle, but the strain levels are lower compared to the PZT materials, which is about 1%. So this has been used as an actuating material and many works have been reported in the literature.

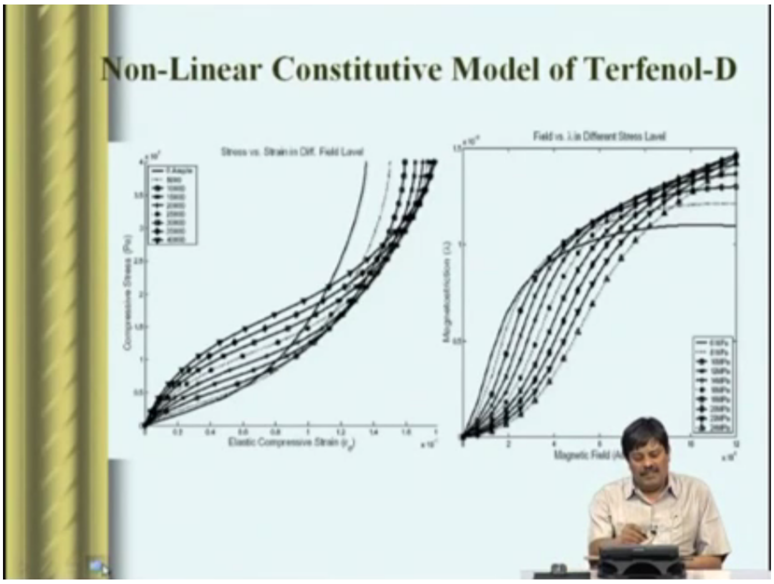
(Refer Slide Time: 46:48)



The next important smart material is the magnetostrictive material. There are many magnetostrictive material, some of them based on magnetic oxide, some of them based on the cobalt oxide, but the most common are extensively used material is one made from Terfenol-D. The Terfenol-D is an alloy of a terbium, which is the rarest of the rare earth iron and it took the name Terfenol because it was actually first made in Naval Ordinance Laboratory in USA.

The terbium is a rare earth material as I said is the rareness of the rare earth material and it is extremely expensive. It is 1 gram of terbium is nearly 8 times the cost of gold, but the major advantage here is it can deliver large strain levels 2% and as a result the amount of control forces that it can generate is of the order of kilonewtons. It has a very low hysteresis hence very effective as an actuator material, but there are some works reported where it has also been used as a sensing material in structural health monitoring studies.

(Refer Slide Time: 48:04)

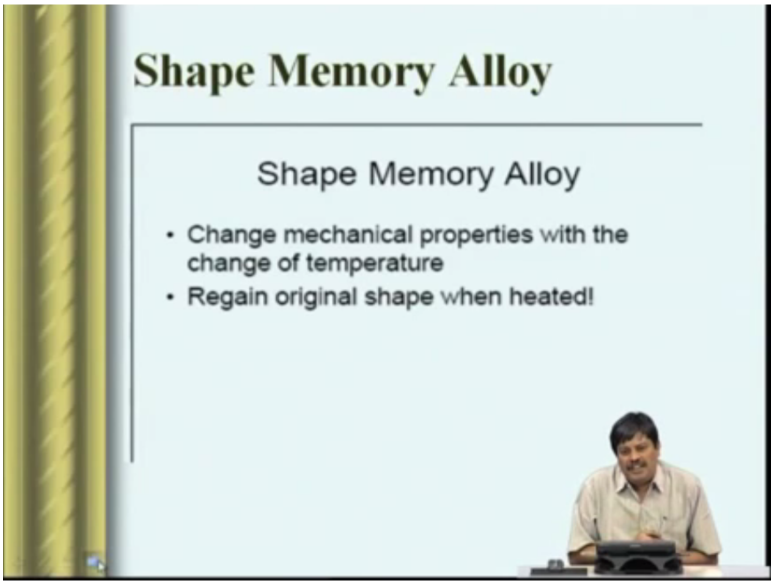


But the major disadvantage with such a material is highly nonlinear material as in the case of PZT material it has 2 constitutive laws, one is the sensor law when a mechanical force is given it generates a magnetic field, which is actually predicted as a current, on the other hand when you feed a current it generates a magnetic field, which would basically strain the material.

So both the sensing and actuation law is highly nonlinear and that is very visible with this view graph, which shows that both the stress strain curve for different magnetic field is highly nonlinear and same the magnetostriction, which is basically represents the sensitivity of the magnetic material with respect to magnetic field for various stress level is also very high.

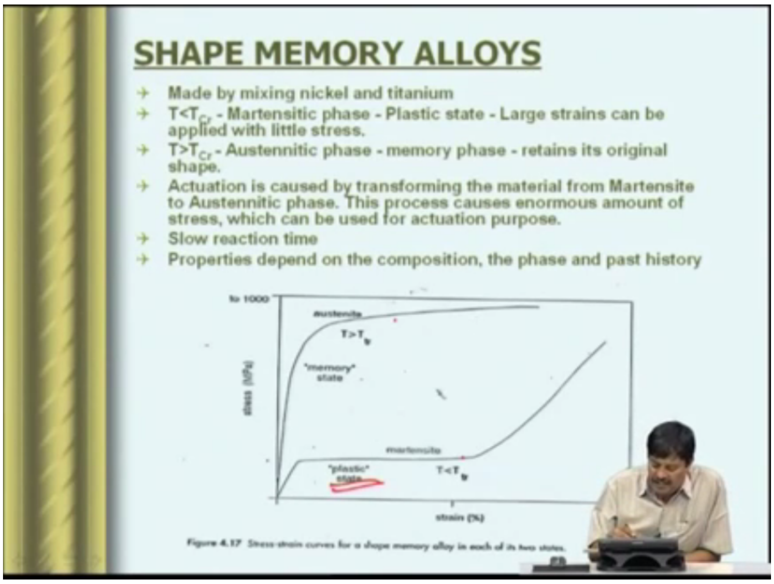
So if you want to find out the critical stresses, we need to take both these sensing and actuation law together to actually get the properties of the material.

(Refer Slide Time: 49:11)



The next material what we are talking is the shape memory alloy and the shape memory alloy basically changes the property with the change in temperature. So basically in the normal temperature, it will be in one phase. When the temperature increases, it goes to the other phase and retains the memory that is precisely it regains the original shape when heated.

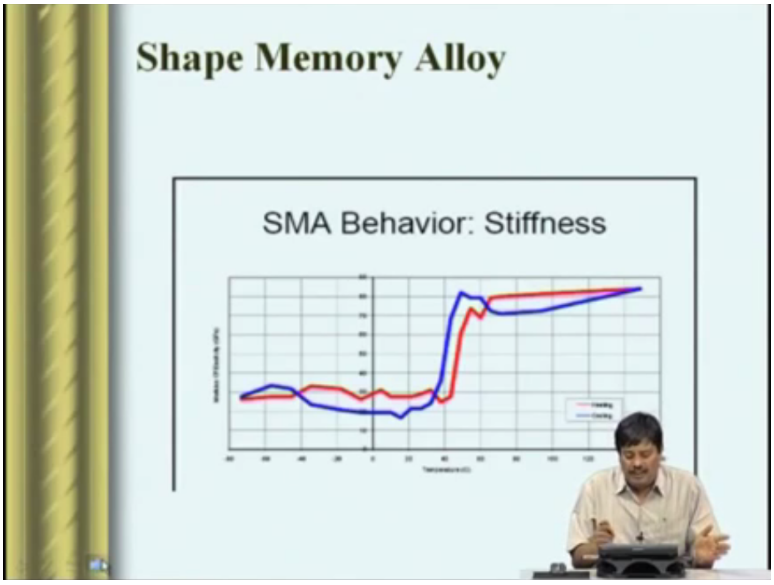
(Refer Slide Time: 49:33)



So if we look at it, in the normal temperature the material is highly plastic, which is shown here. This is a very plastic state then it goes here, but when the temperature increases it goes to the austenite phase. Suppose we actually prevent it the amount of actuation force available is enormous, the amount of stress that is available is enormous, which can be used as actuation.

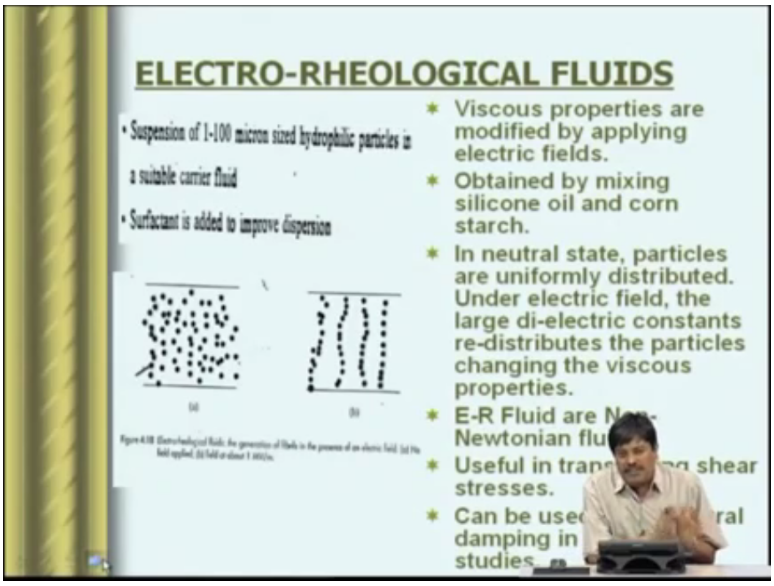
So basically the actuation principle here is basically on the phase transformation from the martensite phase to the austenic phase and the properties depend upon the composition, it is basically made from the mixing nickel and titanium and some amount of copper is also used to actually enhance the performance of these alloys.

(Refer Slide Time: 50:23)



So as I said the stiffness of the material changes with the temperature. Here there are 2 things, the blue is basically tells when it is cool and when the material is heated you see the young's modulus changes. So this change in the behavior of stiffness can be very successful in using for the actuation, but the main disadvantage here is its reaction time is very, very slow.

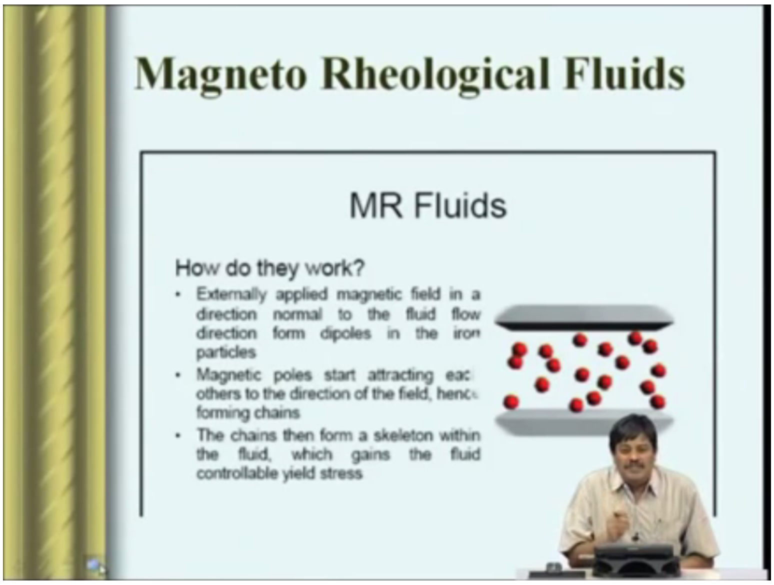
(Refer Slide Time: 50:54)



The next material is the electrorheological fluids. Here a fluid viscosity is basically changed by applying the electric field. So the simplest of these fluids is the electrorheological fluid. It is obtained by mixing silicon oil and the corn starch. It is the cheapest of the smart material. So when such oil is made and when the very high voltage is passed, originally it would be distributed like this and on passing of the voltage, all the particles the silicon oil and corn particles basically orient here to actually change the viscosity of the structure.

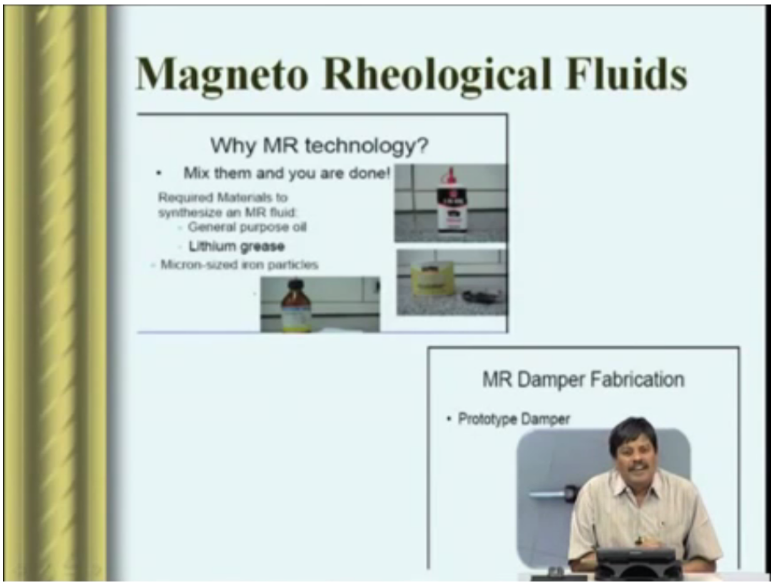
Basically, it is a non-Newtonian fluid hence the analysis of this is much more difficult, however, it is extremely useful as a damping material for vibration control.

(Refer Slide Time: 51:57)



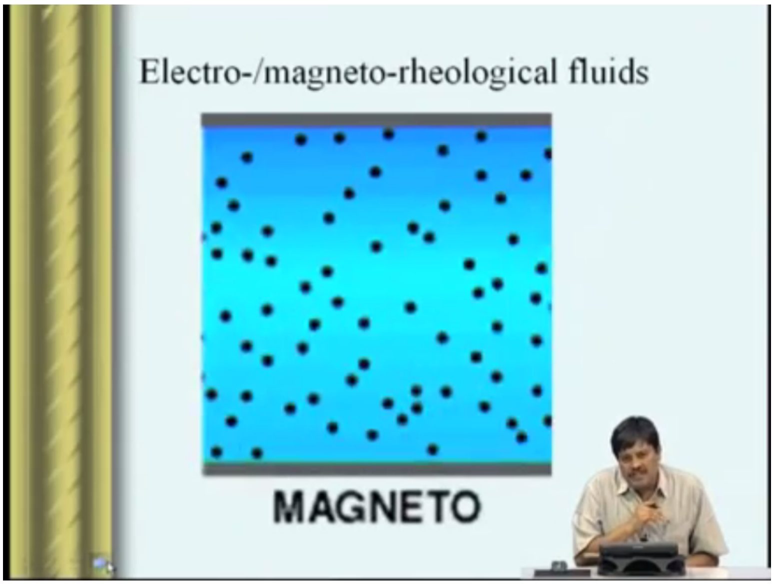
The MR fluids works very similar. MR fluids stands for magnetorhelogical fluids. It works very similar to that of the electrorheological fluids.

(Refer Slide Time: 52:10)



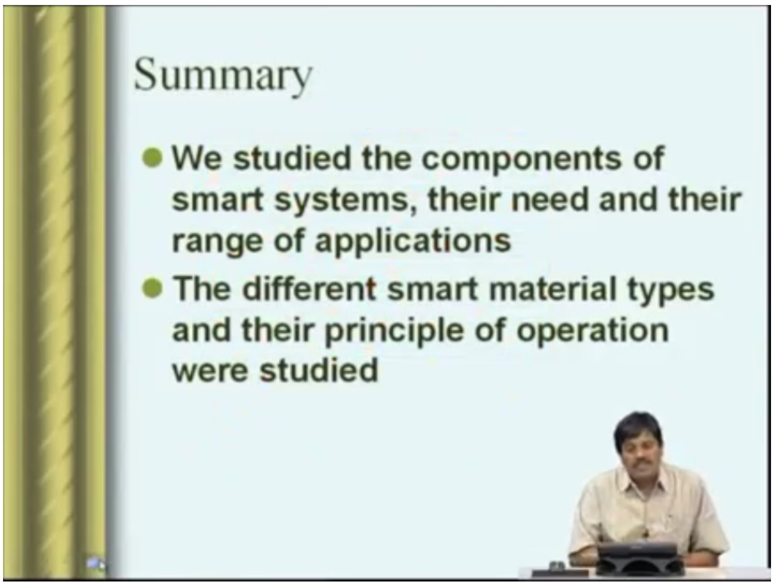
This is basically made from the lithium grease mixed with iron particles. So whenever this is poured all the particles orient together as in the case of electrorheological fluids and changes the viscosity. So basically all these electrorheological and magnetorhelogical basic function is to change the viscosity of the fluid so that by introducing the viscous behavior it can be used for the vibration control application.

(Refer Slide Time: 52:39)



So basically you could see that in this video, how the material which was arbitrary were oriented due to the application of the field. So this clearly says by this process, a fully liquid becomes a semi solid material. So basically it is a smart material that can change the viscosity thereby it can be used for applications involving damping of the structure.

(Refer Slide Time: 53:13)



So basically we conclude this lecture by summarizing what we have done. We have basically studied what are the different components of the smart system, what are the need, the range of applications that this can happen, how the introduction of the smart system has particular benefits to the various branches of science and engineering they say discipline in particular automotive, aerospace, defense etc.

We have also studied what are the different smart material types, their application and operation that we studied here. We also found out the mechanics of operations in many of these smart materials. So the basic idea here is these smart materials can basically induce certain stimulus, which can actually change the properties of the host structure, at the same time when the stimulus is removed, it comes back to the original structure. Thank you.