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

Lecture – 04

Welcome to the course on foundations of cognitive robotics. In the last lecture, we have talked about one of the very important smart materials, which is needed, which is essential for organismoid robot development and that is Shape Memory Alloy.

Today, I will talk about another interesting smart material which is based on polymers and it is predicted that this is the smart material that will be inevitable in terms of the development of cognitive robots. So, let us have a very good discussion on this type of polymeric smart materials today.

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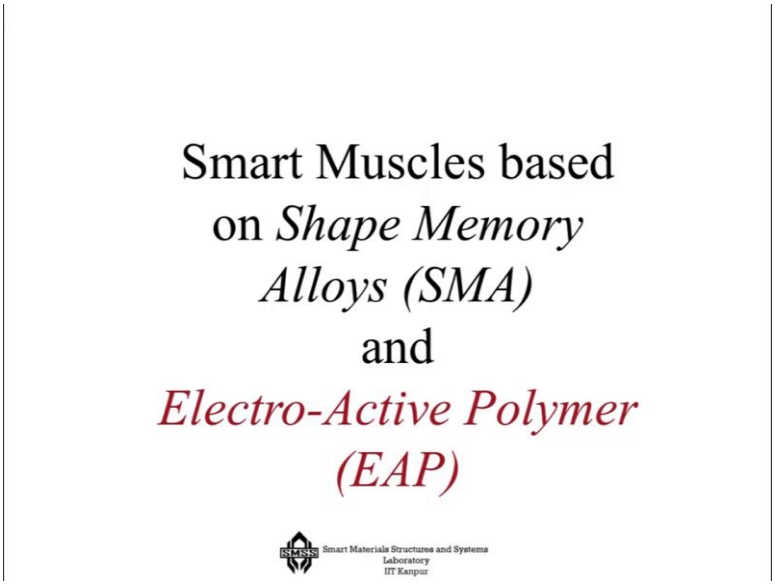

Today, we will talk about the Electro Active Polymers, which is also abbreviated as EAP. Now, this electroactive polymers, they belong to these smart materials group, which is commonly known as active smart polymers.

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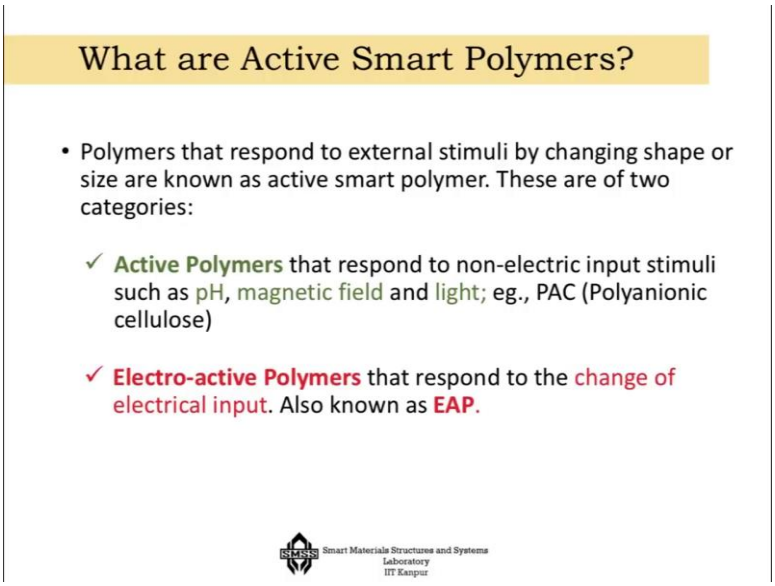

So, what are these active smart polymers? Well, the polymers that respond to external stimuli by changing the shape or size actually known as active smart polymer. So, the output has to be a change of shape or size and the external stimuli could be of different types. In fact, the best way you can differentiate between the external stimuli is that whether it is electrical in nature or non-electrical in nature with respect to these, there are two categories of these active smart polymers.

The first group to be active polymers that respond to non-electric input stimuli, such as pH magnetic field and light one of the example is polyanionic cellulose. Electric field-based actuation of polymer is an even more important step in terms of polymeric development, because you can easily apply electric field on a polymer instead of using other stimuli like; let us say, light or some chemicals and hence in a quick signal based on electricity actuated polymer is a very special class of polymer. This special group of polymer, we will call them as Electro Active Polymers that respond to the change of electrical input it is also known as EAP

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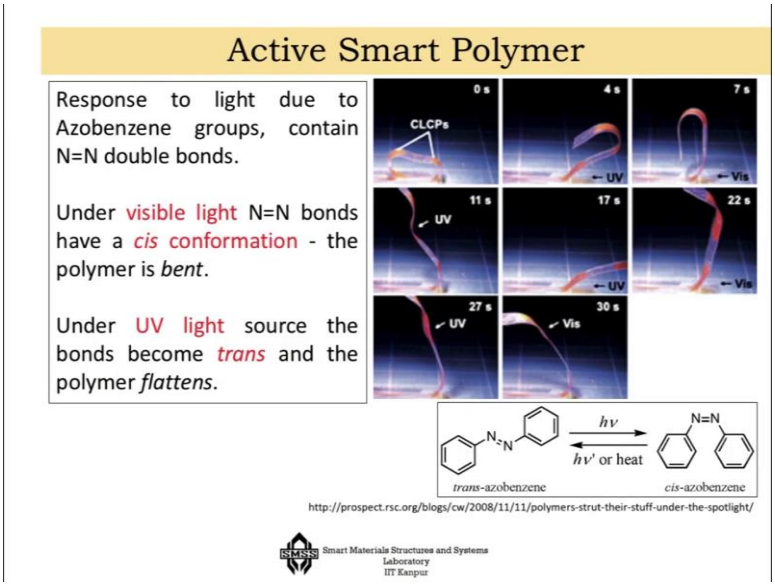

Now, one of the examples of an active smart polymer which is not EAP, but simply active and that is a polymer here as you can see in this particular case and this is a based on Azobenzene actually, and there is a ring-like structure you can see and this response to you know light specifically, light or visible light or UV light and because of the presence of this Azobenzene group in this case which actually contains N=N double bonds. Under visible light, these double bonds have a cis configuration in which the polymer is bent. So, this is the cis configuration you can see these active groups Azobenzene groups here, which are bent.

Now, this is under visible light. The moment we apply UV on it, the part becomes flat. Now, once again, so that means the polymer will be flattening under the UV light. Once

again, you put it under visible light, it will start to bend, and again, if you apply the UV light in the next joint, it will get flattened and again.

So, this is under the visible light and then the UV light, it will once again, it will get actually the flattened and again the visible light the bending will start. So, that is how this whole ring can actually make its movement from one side to the other by successively making its joints transforming between cis and trans configuration. So, this is an interesting case of an active smart polymer.

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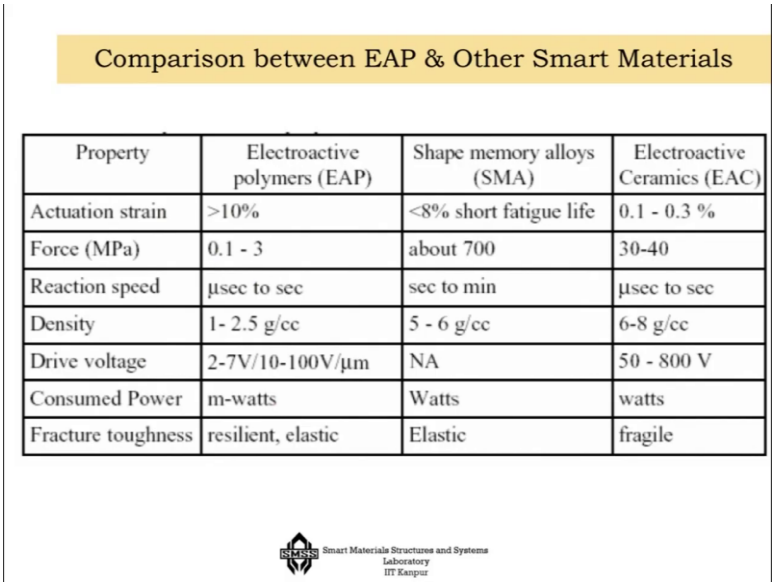

Now, in terms of the electroactive polymers, if we compare the electroactive polymers with the other polymers like shape memory alloys and electroactive ceramics, you would see that electroactive polymers keep the maximum amount of strain that is why we have the highest actually potential of application related to these. It gives about 10 percent of strain as you can see here.

On the other hand, shape memory alloys can give about 8 percent strain and it has a short fatigue life also. So, which means you cannot really use it for a very long time. Active electroceramics that we have earlier discussed gives a much smaller actual percentage of strain even though it does not have, and it does not suffer from a shorter fatigue life.

Now, the only catch is that the force is less here; for example, in terms of stress maximum stress it can generate is about 3 MPa compare that with the shape memory

alloys, which has about 700 MPa and you can easily understand the changes in electroactive polymers is somewhere in between it is having about 30 to 40 MPa.

If you compare the reaction speed, the reaction speed is also equally fast like the electro active ceramics that is between the micro second to second. On the other hand, the shape memory alloys are slower.

They have second to minute reaction speed. Density wise they are very low density from; that is why there is a very low weight penalty by using this type of actuators they are almost close to water density of water in comparison to that SMAs are heavier electroactive ceramics are also heavier.

The driving voltage is not very high it is about two to seven volt whereas, for SMA also it is not very high volt all these not mention here and electroactive ceramics are you require actually quite a very high large voltage.

Now, in terms of the consumed power, you can see that these ones are having about milliwatts of power, whereas all others are required watts of power, which means this leads very low amount of power.

Fracture toughness wise also they are resilient and elastic. On the other hand, ceramics are very-very fragile. So, an overall comparison tells us that these kinds of electroactive polymers are far better placed in comparison to the SMAs or in comparison to the electroceramics as far as we are considering their application in terms of robotics manipulation devices, etcetera. They also have a very interesting history of development.

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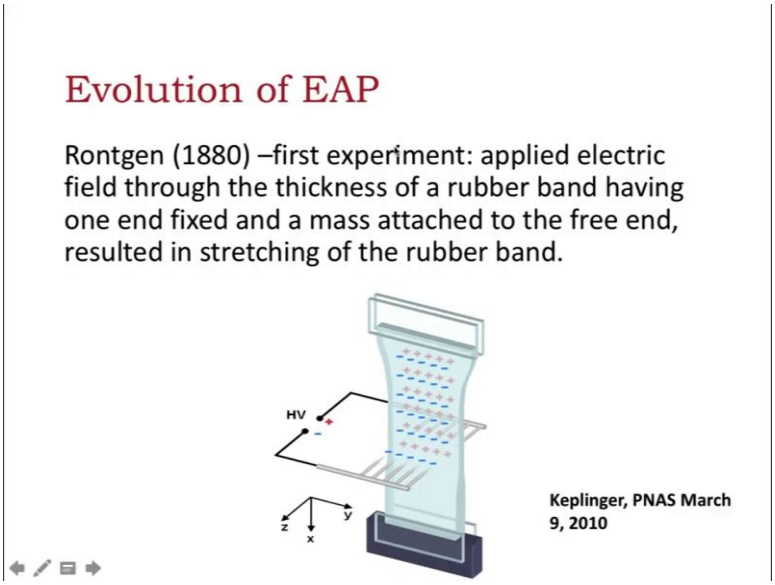

Let us try to see how these kinds of materials have evolved. We will talk about the evolution of electroactive polymer. Now, one of the very important name in this evaluation is Rontgen. You know about Rontgen from his discovery of X-ray for which he got this Nobel prize. Now, in 1880 Rontgen carried out a unique experiment in which he has applied electric field through the thickness of a rubber band having one end fixed like this end is fixed and a mass attached to its other end, the free end and what he found is that as he is applying the electric field, the rubber band is thinning in this section.

You can see that with the help of needle-like probes, he has applied the electric field, and it is thinning in this region and as a result of it, because the rubber is actually incompressible in nature. So, the total volume has to remain the same. So, as it is thinning here, it actually expands in the longitudinal direction.

So, it is thinning and it is expanding, thickness direction its thinning, and it is expanding in the longitudinal direction in order to keep the volume constant. So, that was a very interesting phenomenon that was observed and you know re-discussed by Keplinger in this very interesting PNAS paper in 2010.

Now, that 1880 experiment possibly is the fast on any electroactive polymer. It is also unique ah in terms of the experiment because, in this case, the rubber was you might say like a naked rubber. There is no electrode that was actually there. So, simply directly, the charge is actually provided to the system.

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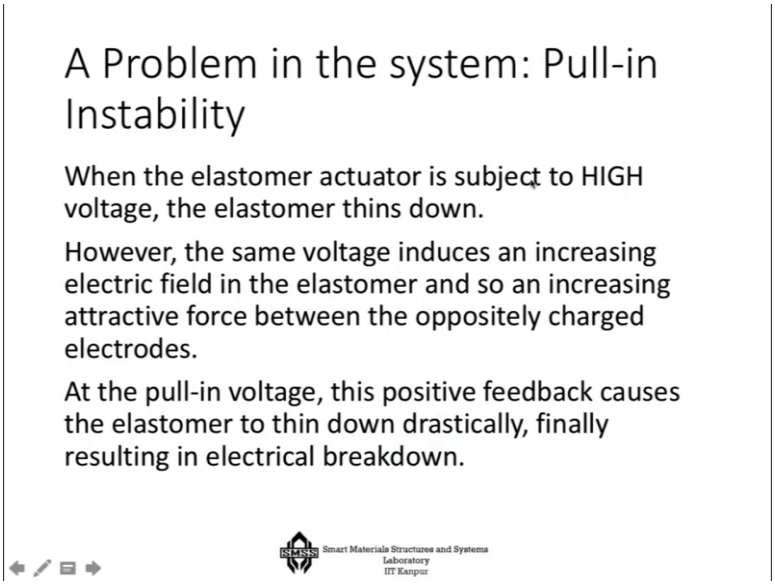

Now, in such systems, there is one danger, however, and the danger is also known as pull-in instability. So, what is this pull-in instability? If I consider an elastomer actuator which is subjected to high voltage, the elastomer will thin down; however, the same voltage induces an increasing electric field in the elastomer and so an increasing attractive force between the oppositely charged electrodes and this oppositely charged electrodes they are basically bringing the two sides closer.

So, that is why it is called the pull-in voltage, and at the pull-in voltage, there is positive feedback that will happen and the elastomer will thin down drastically. Finally, it will result in an electrical breakdown of the system.

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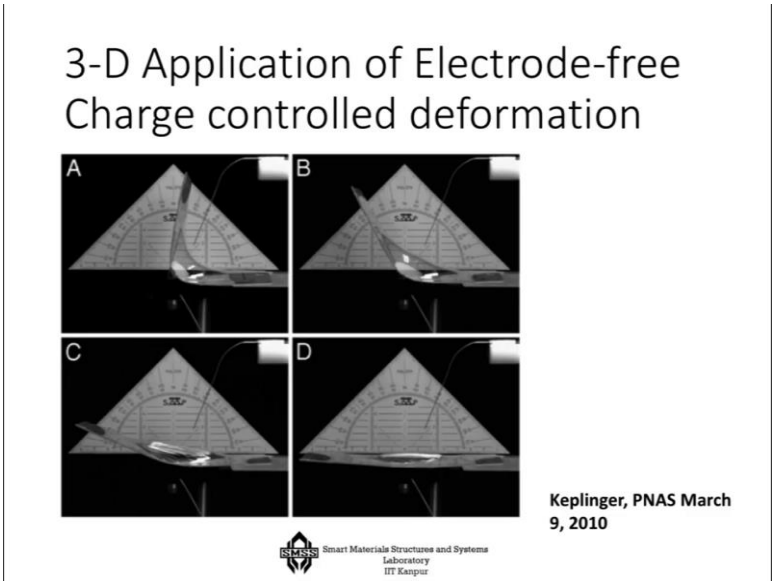

Let us look into some of the other developments. So, as has been shown here by Keplinger in his unique PNAS paper that you can actually develop a 3-dimensional structure based on an electroactive polymer and in these, you do you do not apply any electrode essentially, because the electrodes will create the pull-in instability on the other hand, you apply a high voltage through these needles much the same way as originally Rontgen had planned.

So, you apply the high voltage to the needle and as you can see that as you are applying it, there is expansion happening in the system and you can see that as you are increasing the voltage, you can almost get from an angle to a very flat structure. So, this is something that is kind of a rediscovery of the Rontgen's experiment on an electroactive polymer.

There are many other electroactive polymers which was discovered after Rontgen's discovery. An interestingly, each one of them has a kind of a 50 year approximately time of a frequency between successive discoveries.

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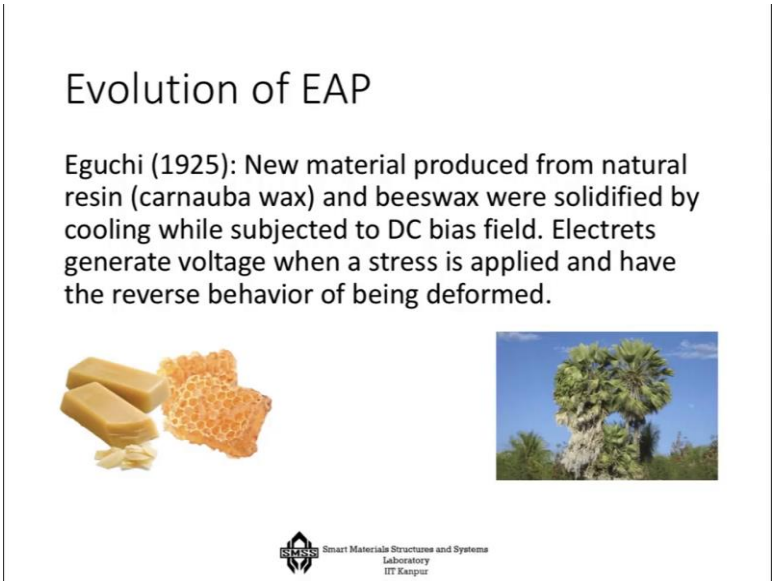

Let us look into those other discoveries of electroactive polymers. In the evolution of EAP, Eguchi's discovery plays a very interesting role. In 1995, Eguchi prepared a new material which is produced from natural resin; it is also known as a Brazil resin from carnauba wax. So, it is a Brazil wax that is how it is generally known as and beeswax. So, he has mixed these two and was solidified by cooling while subjected to the DC bias field and what he noticed is that if this kind of solid electrets. It will generate a voltage when a stress is applied, and it will have the reverse behavior of being deformed.

So, that is what was the discovery of the Eguchi of a new type of you know kind of a polymeric system which is a mix of carnauba and the beeswax which actually shows a high degree of deformation and also, the other effect that is if you know how to apply stress you are going to generate a voltage. You remember we call this to be a direct effect, and we call this one to be a reverse effect. So, both of them Eguchi was able to discover in this particular material.

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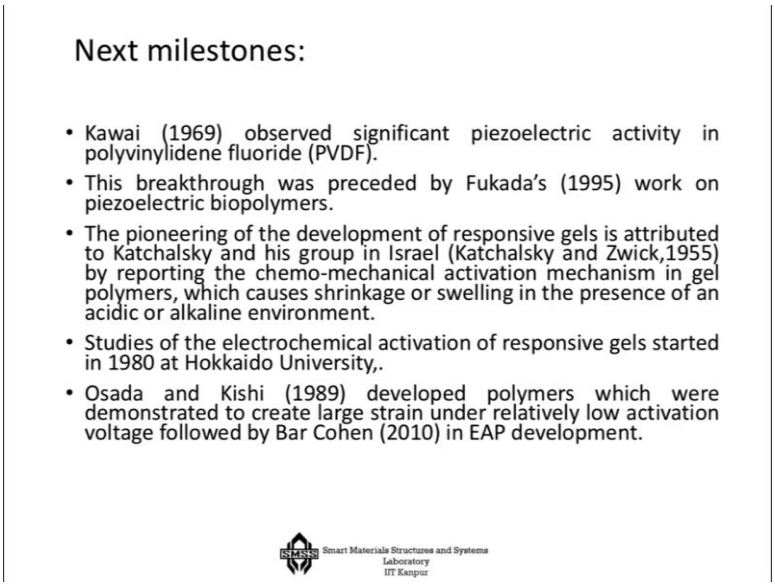

Now, followed by these there are significant discoveries by Kawai in 1969, and this is an entirely new inorganic you may say not exactly you may say that synthetic piezoelectric material. So, this is a synthetic one, because the last one that we had discussed was derived from natural organism material. So, this is a synthetic organic material which is known as polyvinylidene fluoride. In fact, because of the presence of fluorine, some it has some inorganic contributions, but it is a synthetic essentially polymer cis polyvinylidene fluoride and it has shown a large degree of piezoelectric activity.

Now, at a later stage, Fukada actually developed piezoelectric biopolymers on the basis of this PVDF. Another important landmark was from the Katchalsky and his group in Israel, who have developed actually responsive gels, but these gels were mostly chemo mechanically activated. So, these are gel polymers and this shows a very high degree of shrinkage or swelling; that means there is a bulk volume change in the presence of an acidic or alkaline environment.

Now, joining these two concepts, in 1980, Hokkaido University, people have first developed responsive gels that are based on electrochemical activation and following that line subsequently, Osada and Kishi developed in 1989.

They have developed polymers that can demonstrate very large strain under relatively low activation voltage, which was followed by Bar-Cohen in 2010, in terms of the development of electro active polymers on a specific polymeric system called Nafion.

Now, the question is; where am I going to use this kind of an electroactive polymer? Why are they where I am repetitively telling that it is so important in terms of robotic development. Well, one of the very important applications of this type of polymer is in terms of locomotive, locomotions or generation of locomotive forces. So, let us look into that how in robotics you know gradually, this transfer from the motor to motorless locomotion has taken place.

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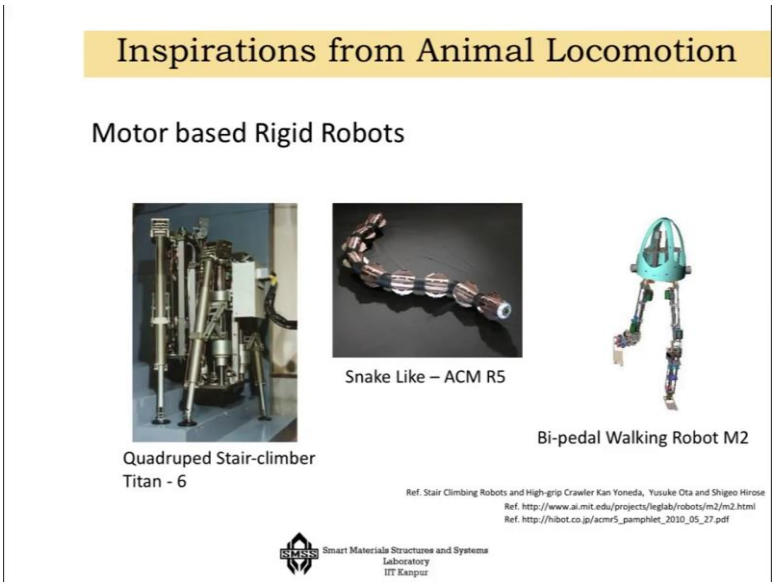

If we look into the animal locomotion based inspirations, you will see that starting from the motor based rigid robots like this kind of a Quadruped Stair climber Titan-6 or a snake-like ACM R5 or for that matter a Bi-pedal Walking Robot M2.

We have also seen Asimos, which are all basically motor-driven some of them are servo motors or other Russell's DC motors, but these are all motor driven systems, but taking inspiration from animal locomotions. Gradually, these locomotions have been achieved in a different manner.

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This different manner is if you study the animal locomotion, you will see that they essentially use muscles for actual motion and we will call it actuation. Now, these muscles are attached to bones by the tendons, and the muscles contract to move our bones by pulling on them.

So, you have to keep in mind that these muscles can only contract and hints; they can only pull; they cannot push. So, that is one of the important aspects to be kept in mind. So, this is why in any joint, the muscles are used in pairs; one muscle of the pair contracts to move the body part and the other muscle at that time actually relaxes and later on the other muscle actually contracts to return the body part back to the original position. So, the muscles that work like these are called antagonistic pairs. So, we have basically two types of muscles called agonist muscle and antagonist's muscle.

If you look at your own elbow for example, what you will see is that in our own elbow, if we actually move our arm, if let us say that we want to pull our arm, you would see that this is the part which is pulling. So, this is the part which is actually, agonist you know the muscle and the back part is actually the antagonist.

So, that is how the motion of this a joint is actually happening by constantly the pulling of the two biceps and the triceps muscle. So, it is a very similar kind of a concept that we will be actually applying in the case of the smart muscles also.

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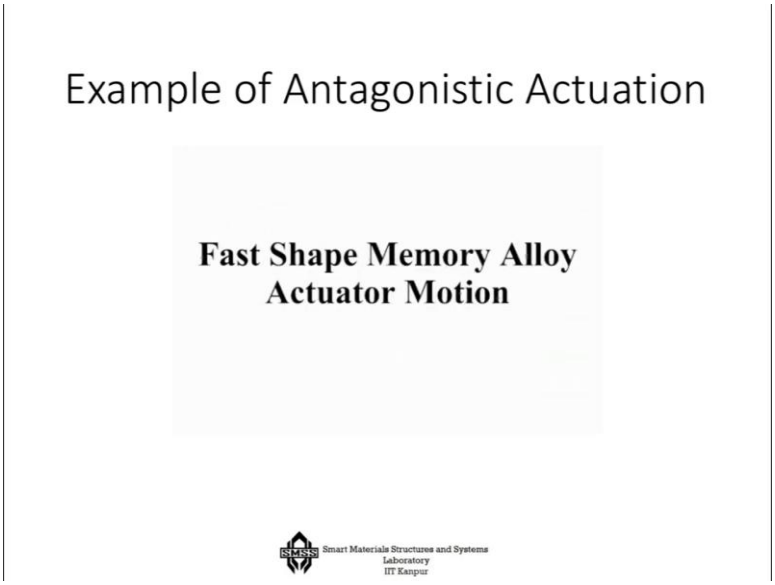

Let us see how we can apply this antagonistic actuation by using shape memory alloy. Now, here is an example in which people have developed a shape memory alloy-based agonist and antagonist motions.

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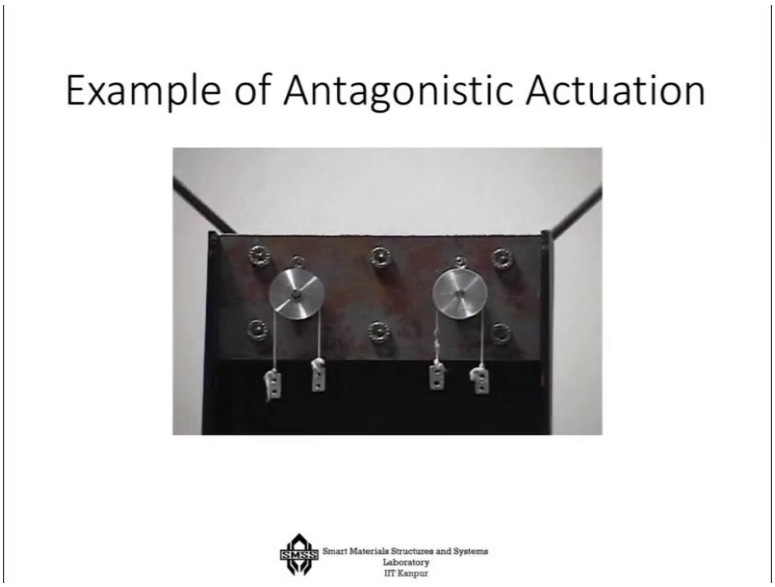

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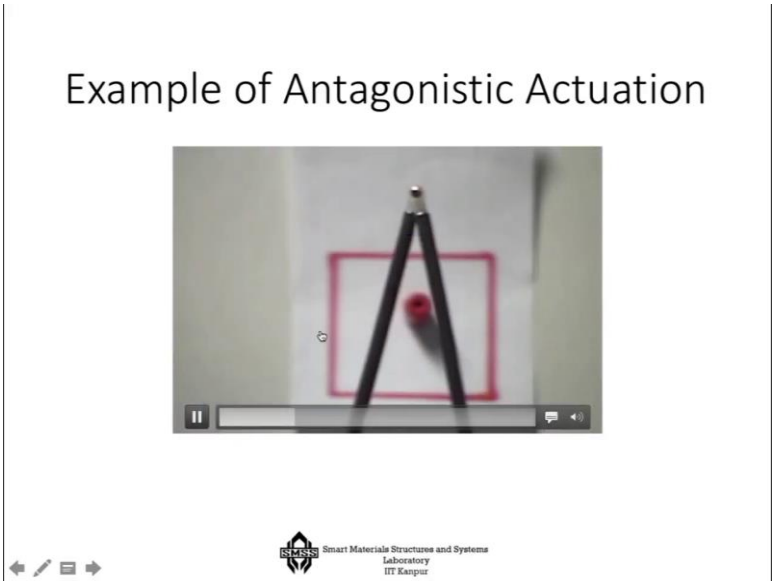

So, the whichever is pulling is an agonist and the other one is relaxing. So, antagonist and look at the trajectory that it is creating. So, the other side you have seen that agonist and antagonist motion and you can see here that it is a nice rectangle that has been drawn. Very similar things are done for almost all our muscles and by varying these pairs motion, you can actually do it faster or slower.

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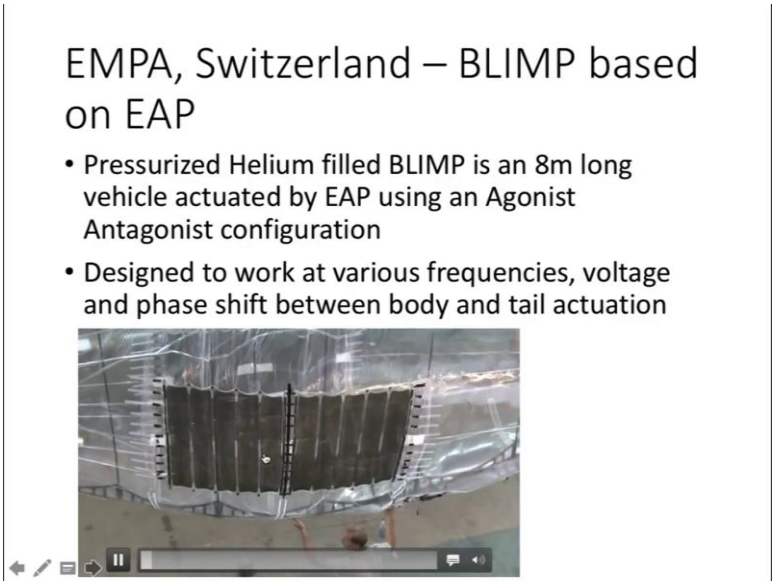

There is another very interesting application of this agonist-antagonist motion. By using actually electroactive polymers by a group in Switzerland EMPA group and they call this

to be BLIMP. So, this BLIMP is essentially a Pressurized Helium filled, it is a big fish that is like eight meters long and it is actuated by electroactive polymer using this agonist-antagonist configuration and it is designed to work at various frequencies voltage and phase shift between the body and the tail actuation.

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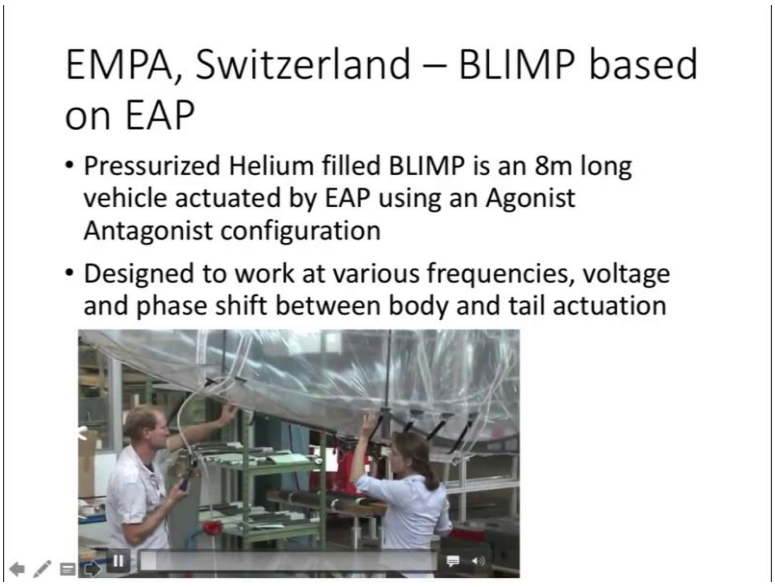

So, you can see that this is an 8 meter big and you can see these muscles, you know which is it is a very flexible inflated structure.

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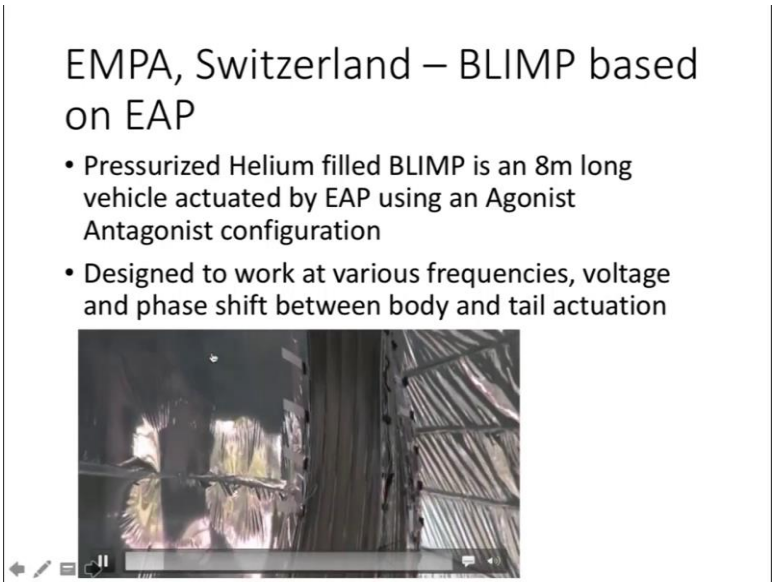

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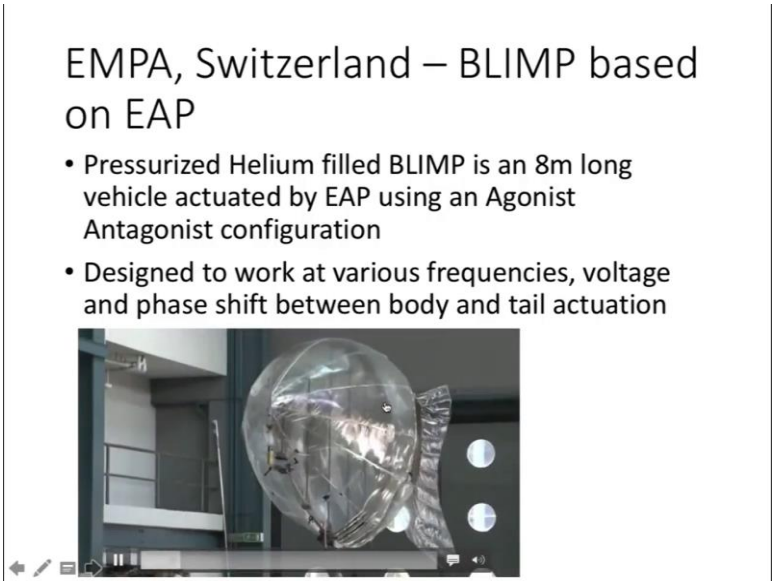

So, first they are pressurizing helium gas into it and you can see that how these muscles are working here and you can see that by these you know agonist-antagonist working of the BLIMPs EAP electroactive polymers, how they are very nicely you know moving the tail as well as the body in the space and is generating the motion.

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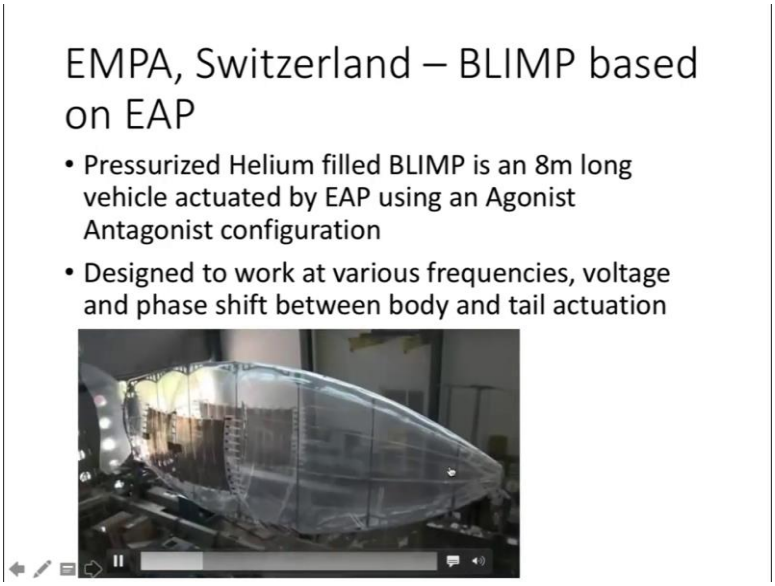

If this is in the laboratory, you can see how this motion is happening, also they have tested such a system in outdoor. So, you can say that this is possibly the fast organismoid

robot, which is a fish-like robot which is based on the muscles that are essentially, bio-inspired in nature. You can see the electroactive polymers here.

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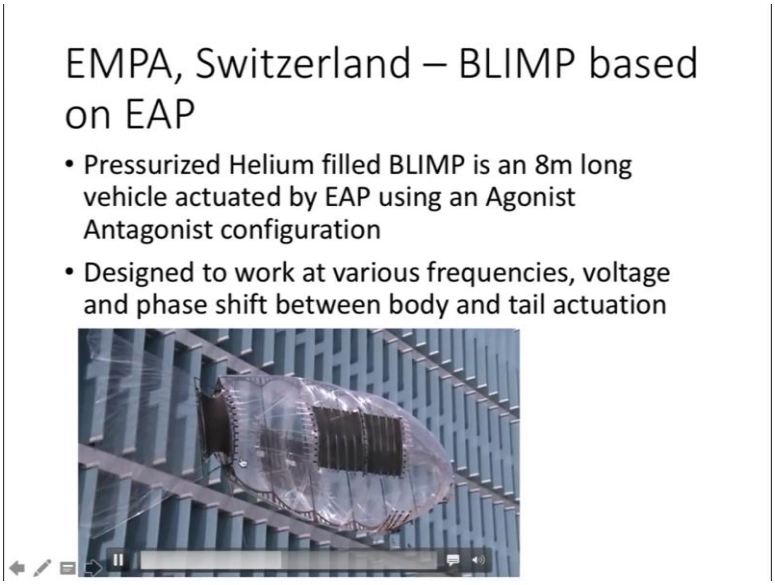

So, this is where they are actually testing this entire system outside, and you can see how nicely this is manual varying controlling its position. So, that is one of the examples of the electroactive polymers.

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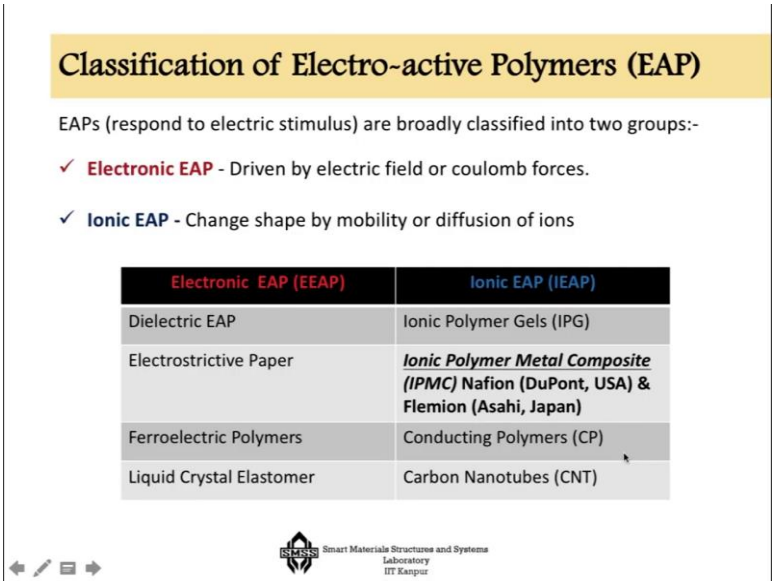

Now, we will talk about some of the classifications of the electroactive polymers that they themselves can be grouped into two types; Electronic EAP, which is driven by

Electric field or Coulomb force, and Ionic EAP, which changes the shape or by mobility or diffusion of actually ions. So, as the name itself is suggesting and it is also any true that electronic EAPs are much faster, the Coulomb force-based EAPs whereas ionic EAPs are actually slower because they depend on the mobility or the diffusion of the ions, which is a slower process, but of course, they can generate a much larger change in the system.

Now, electronic EAPs, which is also known as EEAP, they are like dielectric EAP one of the example, another is electrostrictive paper, ferroelectric polymer, and liquid crystal elastomer. On the other hand, the IEAPs are like ionic polymer gels, ionic polymer-metal composite like; IPMCs, Nafion, Duponts, Flemion, etcetera, then there are some conductive polymers and even carbon nanotubes. So, these are the groups which show the ionic electroactive polymer

We will now focus on the ionic electroactive polymers because, as I told you that they are the best performing material as far as the large deformation goes and also as far as the power consumption goes.

They consume very little amount of power, and so they have a real future in terms of developing different types of motions in robotic, you know limbs or so-called arms and legs of a robot. So, let us look into the ionic polymer matrix composites or this kind of you know ionic electroactive polymers.

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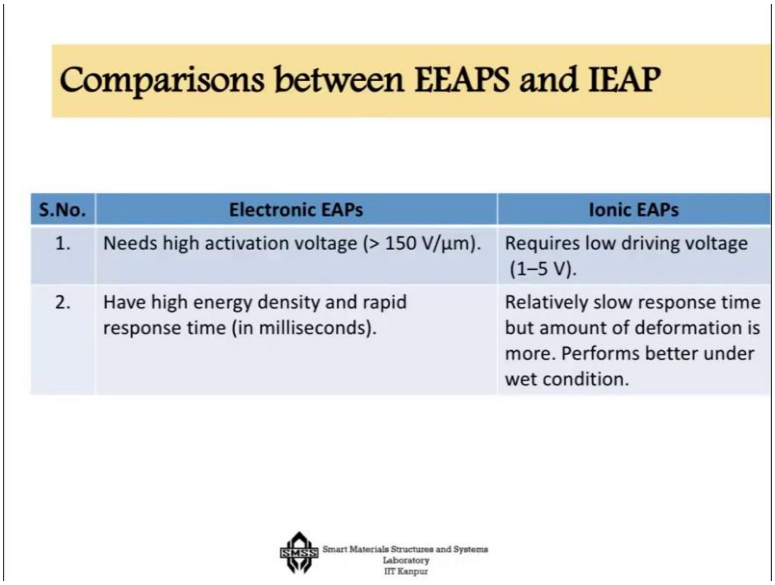

If I compare between the EEAPS and IEAPs, that is what I was telling you that EAPS needs a high activation voltage whereas ionic EAPs need very low voltage and they have this EAPs have a high energy density and rapid response time in comparison to these IEAPs have relatively slow response times, but the amount of deformation is much more and they perform better under wet condition.

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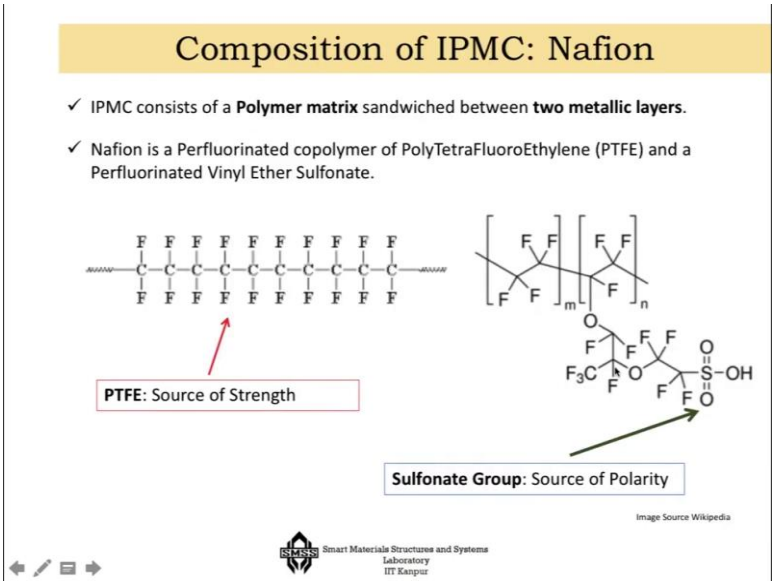

So, if you look at one of these ionic electroactive polymers, which is IPMC that is ionic polymer-metal composite, the example here is the Nafion. Now, this type of material actually consists of a Polymer matrix that is sandwiched between two metallic layers. Now, Nafion specifically is actually a Perfluorinated co-polymer of PolyTetraFluoroEthylene or PTFE and a Perfluorinated Vinyl Ether Sulfonate. Now, you have actually come across PTFEs in your day to day life when we talk about non-stick pans, etcetera.

So, PTFE actually gives the strength to the material. So, PTFE is one part, as I told you, there is a co-polymer. So, one co-polymers are made of two polymers. So, one part is PTFE, which gives them strength and the other part is this perfluorinated Vinyl ether sulfonate. So, this perfluorinated vinyl ether sulfonate, which is heavily fluorinated essentially and it has a sulfonate group, that sulfonate group is actually the source of polarity in the system and note down that these perfluorinated groups have OH^- in it. So, it means that it has a fixed OH^- attached to it always ok.

So, this is. So, if you have a material which is these a combination of the two and then if you put them in an electrode, then you can generate a fixed negative charge on one side.

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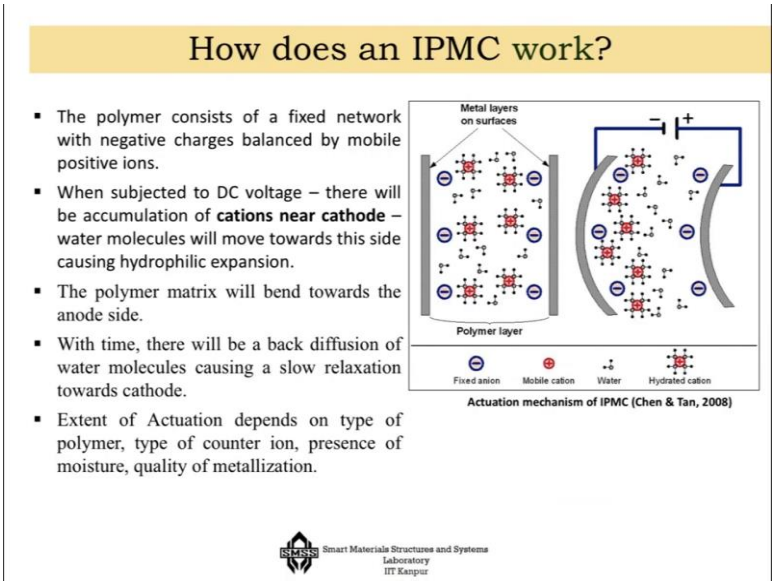

So, you can see here that there is this electrode here, and there are these fixed negative charges, which is generated with the help of the sulfonate groups. Now, these fixed negative charges, the moment I attach these cathodes, what will happen is that the water molecules that is present inside the IPMC they will start to go towards, massively towards these negative, you know the direction the cathode.

So, as there is the driving of the water molecules, this side will bend; if there are more water molecules, one side will bend know. So, probably this what you are getting a bent thing and with respect to time, some water molecule will back diffuse, which actually talks about a relaxation.

So, a small relaxation will happen, but essentially you can generate a large bending in this kind of materials, but of course, one of the precondition is that it needs to be wet because then only the water molecules movement towards these cathodes will create this large hydrophilic expansion in the system.

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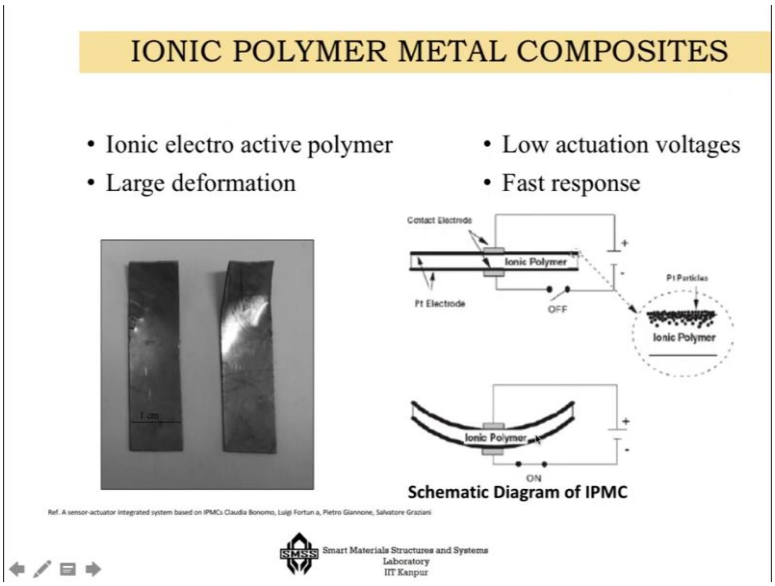

Now, depending on the type of electrodes, you can actually generate the positive and negative bending in IPMCs. So, as you can see that this is a kind of a typical IPMC that is how it looks like under the normal condition and under the bent condition, and you can get a large deformation out of this system and with a low actuation voltage and fast response.

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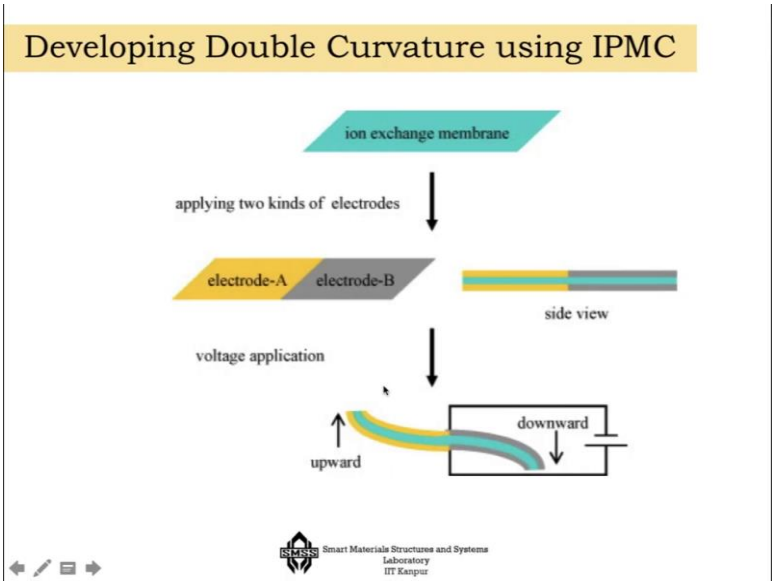

You can actually generate by changing two different types of electrodes on an IPMC, you can generate two different types of curvatures in it, you can generate a downward

and you know this downward and an upward kind of curvature. So, you can generate double curvature in the system by using two different types of electrodes in the system. So, that is one of the advantages of the system.

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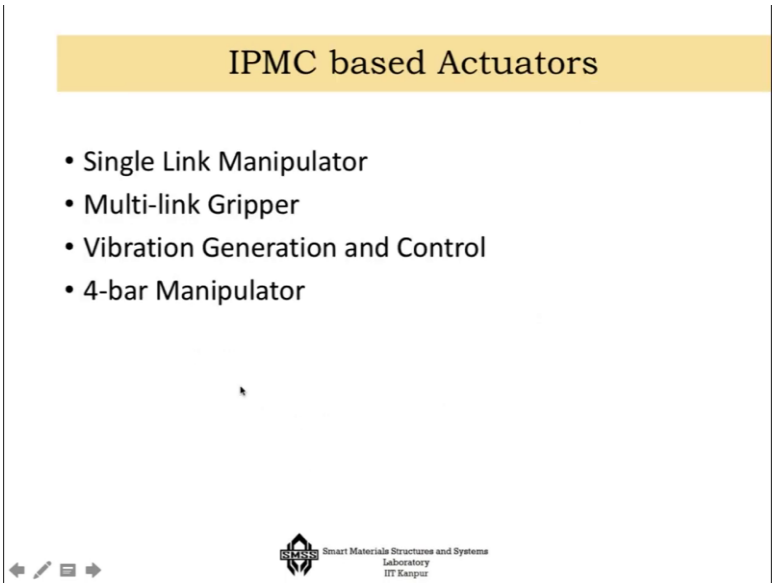

Now, this kind of IPMC based actuators they are used for single link manipulators, multi-link grippers', vibration generation control, and 4-bar manipulator. So, most of the locomotion generation can be done with the help of this type of IPMC based actuation system.

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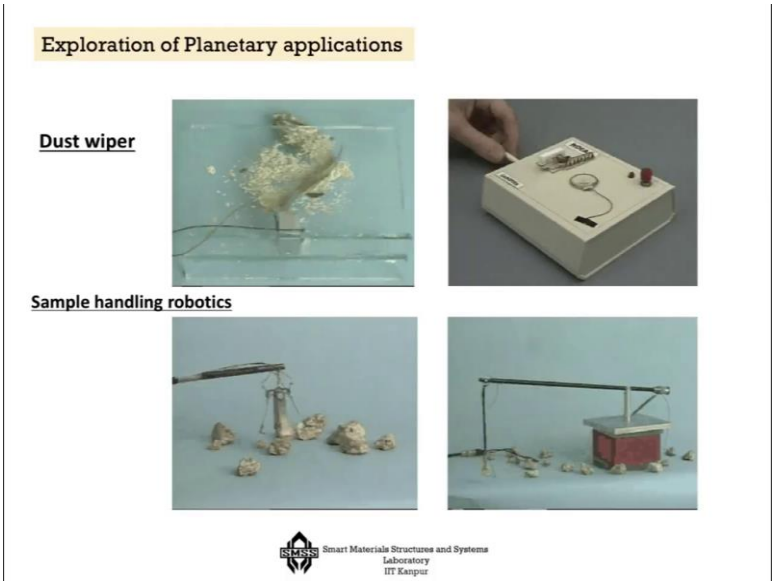

So, some of the applications you can see that like this is in terms of a dust wiper, you can see that how this dust wiper actually works in terms of cleaning in fact, the last reformation and then there are other applications also like these sample handling, in robotics, this I already told you in different applications are possible or particularly for the planetary applications people have already used this type of electroactive polymers.

Now, I will just conclude this particular session of the lecture by comparing, because we now are in a process that we can summarize actually, that the different smart materials via the biological system in terms of their performance. So, this is what we will be doing in the final concluding slides.

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Advantages and Disadvantages of the Two EAP Groups Relative to Mammalian Skeletal Muscles

Actuators	Advantages	Disadvantages	Comments
Mammalian skeletal muscle	• Large strains (20%) • Moderate stress (350 kPa blocking) • Variable stiffness • High-energy fuel (20–40 MJ/kg) • Efficient (~40%) • Good work density (<40 kJ/kg) • High cycle life (by regeneration)	• Not yet engineering material • Narrow temperature range of operation • No catch state (expends energy to maintain force w/o moving)	• Muscle is a three-dimensional nanofabricated system with integrated sensors, energy delivery, waste/heat removal, local energy supply, and repair mechanisms
Field-activated (Electronic) Group			
Field-activated (electronic) group	• High mechanical energy density • Relatively large actuation forces • Can operate for a long time in room conditions • Exhibits rapid response (ms) • Can hold strain under DC activation	• Produces mostly monopolar actuation • Requires high voltages (~100 MV/m). Use of additives enabled reduction of the field in Ferroelectric EAP	
Dielectric elastomers	• Large strains (20%–380%) • Moderate stress (several MPa peak) • Large work density (10 kJ/m^3 to 3.4 MJ/m^3) • Moderate to high bandwidth (10 Hz to >1 kHz) • Low cost • Low current • Good electromechanical coupling and efficiency (>15% typical, 90% max)	• High voltages (>1 kV) and fields (~150 MV/m) • Typically requires DC–DC converters • Compliant (E ~ 1 MPa) • Prestretching mechanisms add substantial mass and volume, reducing actual work density and stress. The recent development in IPNs is helping to overcome this disadvantage	• Potential to lower fields using high dielectric materials • Based on readily available materials
Ferroelectric polymers	• Moderate strain (<7%) • High stress (45 MPa blocking) • Very high work density (up to 1 MJ/m^3 internal strain) • Stiff (400 MPa) • Strong coupling (0.4) and efficiency • Low current	• High voltages (>1 kV) and fields (~150 MV/m) • Typically requires DC–DC converters • Cycle life is unclear and may be limited by electrode fatigue and dissipation • Synthesis of typical materials involves environmentally regulated substances • Limited temperature range	• Lower voltages and fields are being achieved using new high dielectric composites • Small devices are favored for high-frequency operations • Unique combinations of high stiffness, moderate strain, and reasonable efficiency

continued

From: Yoseph Bar Cohen: Bio-mimetics – Nature based Innovation

If I compare mammalian skeleton muscles with initially, the field activated electronic electroactive polymers, and then we will compare them with the other groups of ionic electroactive polymers. Now, the mammalian skeletal muscles produce large strains. How large? We always say large in the quantification here is about 20 percent and the stress is; however, moderate about 350 kilo Pascal, stiffness can be varied, but the fuel that is used in terms of the nutrition that is a high energy fuel, efficiency is near about 40 percent, and they have a good work density about 40 kilo Joule per kg. They have a high cycle life because they can actually regenerate also.

The disadvantage is that; this type of material is not an engineering material, and they have a narrow temperature range of operation in the high temperature, they cannot work,

and they expend energy to maintain force you know without moving. So, that is one of the problems that they do not have any catch state.

Now; however, an interesting thing to learn is that they have a very interesting 3-dimensional system that integrates both the sensor, energy delivery, waste heat removal, local energy supply, and repair mechanisms, all in one pack. That is something that kind of compactness we are still not able to achieve as far as the synthetic you know materials are concerned.

Now, let us look into the field activated electronic groups fast among the synthetic materials. The first group is the field activated electronic group like PVDF, high mechanical energy density relatively large actuation force, in the mega Pascal range can operate for a long time in room condition and rapid response about millisecond range and can hold strain under DC activation. So, they are all electrically activated. The disadvantage is that the product is mostly the monopolar type of actuation, and it requires a high voltage. So, high voltage is the real disadvantage of the system.

In comparison to that, if I consider the dielectric elastomers like some of the examples I told you in terms of Rontgen's initial experiment and the other elastomers, they can actually show large strains. It can be as large as up to 380 percent, much larger than the mammalian skeletal muscles. So, that is what is very large stress is moderate only several MPa, but still, it is comparable with respect to mammalian muscle large work density and moderate to high bandwidth, not very high bandwidth this has a very high bandwidth the field activated groups. Low cost, low current, and good electromechanical coupling.

Now, what is the disadvantage? You need to generate high voltage, locally, of course, typically requires a DC-DC conversion, and it is quite soft, pre-stretching mechanisms add substantial mass and volume because pre-stretching is important in terms of its movement. You remember that in the initial Rontgen's experiment, there was a mass that was used to prestretch the rubber band. Now, there is potential to lower fields using high dielectric materials and based on readily available materials. So, this is a good one, but still, it has certain disadvantages.

If I consider the ferroelectric polymers, then the strain level is less, only about 7 percent, stress is high 45 MPa blocking stress relatively high, you know much-much higher in

comparison to these, which is in kPa range very high work density, stiff and strong coupling. It also requires high voltage, and the cycle life is one of the problems because there is some fatigue that is observed, and it has a limited temperature range. So, here the lower voltage and fields people are trying to achieve now, you know in the ferroelectric polymers and the energy density is in favored and small devices with high frequency in something that is under focus.

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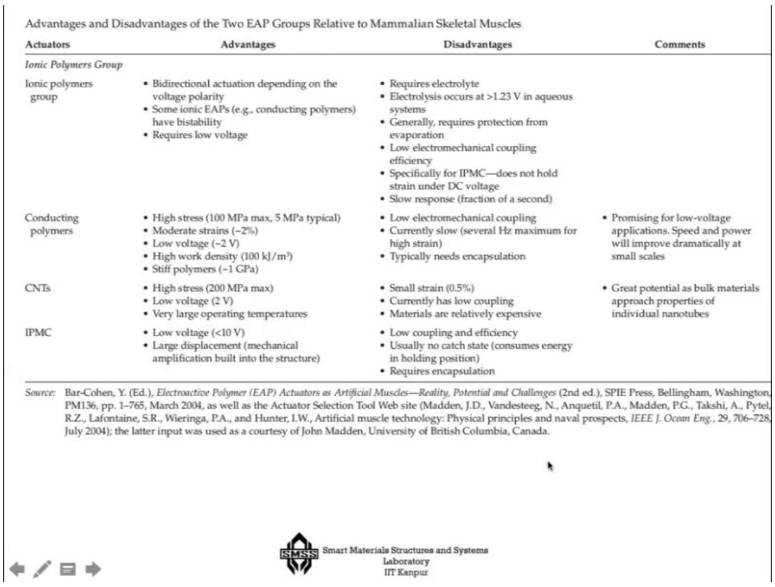

Advantages and Disadvantages of the Two EAP Groups Relative to Mammalian Skeletal Muscles

Actuators	Advantages	Disadvantages	Comments
Ionic Polymers Group			
Ionic polymers group	• Bidirectional actuation depending on the voltage polarity • Some ionic EAPs (e.g., conducting polymers) have bistability • Requires low voltage	• Requires electrolyte • Electrolysis occurs at >1.23 V in aqueous systems • Generally, requires protection from evaporation • Low electromechanical coupling efficiency • Specifically for IPMC—does not hold strain under DC voltage • Slow response (fraction of a second)	
Conducting polymers	• High stress (100 MPa max, 5 MPa typical) • Moderate strains (~2%) • Low voltage (~2 V) • High work density (100 kJ/m³) • Stiff polymers (~1 GPa)	• Low electromechanical coupling • Currently slow (several Hz maximum for high strain) • Typically needs encapsulation	• Promising for low-voltage applications. Speed and power will improve dramatically at small scales
CNTs	• High stress (200 MPa max) • Low voltage (2 V) • Very large operating temperatures	• Small strain (0.5%) • Currently has low coupling • Materials are relatively expensive	• Great potential as bulk materials approach properties of individual nanotubes
IPMC	• Low voltage (<10 V) • Large displacement (mechanical amplification built into the structure)	• Low coupling and efficiency • Usually no catch state (consumes energy in holding position) • Requires encapsulation	

Source: Bar-Cohen, Y. (Ed.), *Electroactive Polymer (EAP) Actuators as Artificial Muscles—Reality, Potential and Challenges* (2nd ed.), SPIE Press, Bellingham, Washington, PM136, pp. 1–765, March 2004, as well as the Actuator Selection Tool Web site (Madden, J.D., Vandesteeg, N., Anquetil, P.A., Madden, P.G., Takshi, A., Pytel, R.Z., Lafontaine, S.R., Wieringa, P.A., and Hunter, I.W., Artificial muscle technology: Physical principles and naval prospects, *IEEE J. Ocean Eng.*, 29, 706–728, July 2004); the latter input was used as a courtesy of John Madden, University of British Columbia, Canada.

Let us look into the other group, the ionic polymer group, which we have discussed at the end. They have bidirectional actuation, and they have bistability, and they require low voltage. Now, this bistability is a fascinating concept. It means that this kind of structure can have two different stability configurations, and it can very fast switch between these two different stability configurations.

The disadvantage is that they always require some electrolyte because there is some movement of the ions that have to occur, voltage requirement is not very high, but this electrolyte presence is significant under wet conditions. Generally, that is why it requires protection from evaporation, low electromechanical coupling, and specifically for IPMC does not hold strain under DC voltage.

For conductive polymers they can generate high stress, but the strain is moderate-low voltage, and these are stiffer polymers, but they have low electromechanical coupling,

which means not much of electrical energy will be converted to mechanical energy. They are promising for low voltage applications.

Also, there are CNTs which require which gives a high-stress low voltage, but the strain is low, and IPMCs which actually takes low voltage, very low voltage, and large displacement, but it has a low coupling in terms of efficiency, and usually it has no catch state; that means, consumes energy in holding position and requires encapsulation, but it has a great potential as bulk material you know properties you know they can be actually improved due to individual nanotubes. So, this is a comparison between all the different types of these electroactive polymers versus the muscles.

So, with this lecture, I will conclude the smart materials and their applications in terms of the development of organismoid robots. In the next series of lectures, we will look into the cognitive aspects of the system, and particularly we look into the living system and the cognitive aspect of it, but we will start with the say, for example, the description of the highest, you know you know in terms of the cognitive capabilities that is the brain itself. So, we will discuss these parts and because that is also an essential element in our organismoid robot development.

Thank you.