Micro and Smart Systems
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Lecture – 04
Microactuators

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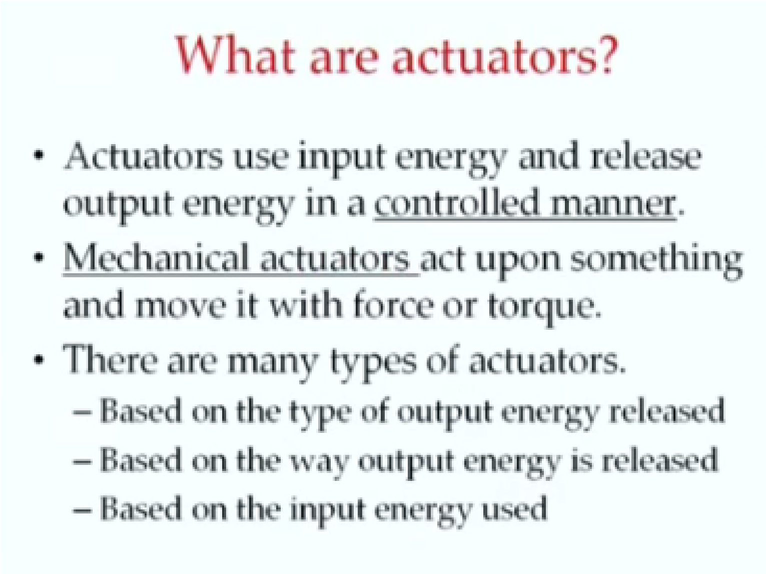

Hello, today we are going to discuss micro actuators. This is the 4th lecture in the micro and smart systems course, we had one lecture on sensors; micro sensors. Today, we are going to talk about the actuators. So, first let us define what actuators are; everybody has a notion of what actuations is, but let us look at a more inclusive definition of actuators. Actuators use input energy and release output energy in a controlled manner.

The controlled manner is the key here because if you say an input energy is released as output energy even an explosion can be considered an actuation, it could be an actuation but for us, an actuator is something that take some input energy and releases as output energy in a controlled way, so that that is the kind of the energy that we would like to have in a particular application. We have a more general definition here to define actuator this way.

That is; it just gives output energy in a controlled way taking some form of input energy but generally, we have a notion of actuators as for example; as mechanical actuators those that act upon something and move it with some force over certain displacement. It need not be only a force, it can also be a torque, so a mechanical actuator is something that causes a body, it can be a solid or it can be a fluidic body or that is a gas or a liquid.

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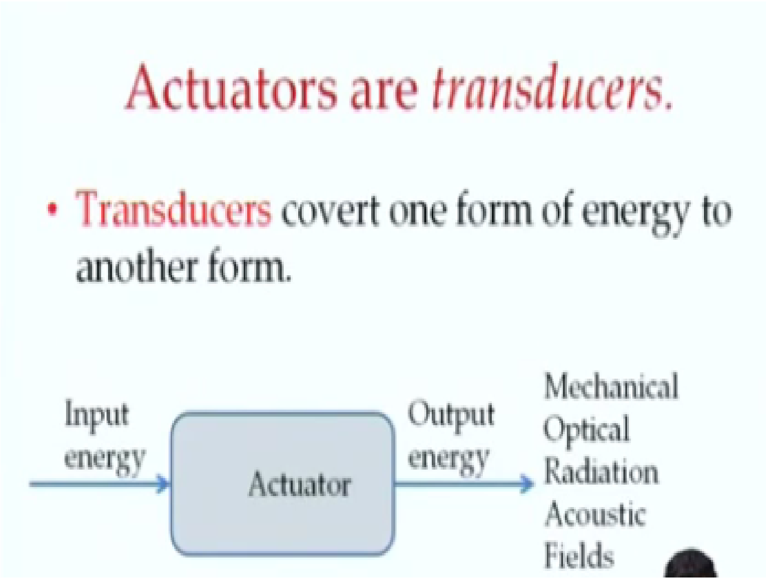

But it moves that over a distance with certain force. There are lots of different kinds of actuators that one can imagine. If you want to classify all of them, we can do that based on the type of output energy released and also based on the way the output energy is released and also based on the input energy used to produce the output energy. Let us look at some examples. First of all, before we consider the examples, let us look at actuators and sensors as transducers.

Because, both sensors and actuators convert one form of energy into another form, so if I have an actuator here as it is shown here, there is some input energy that it takes and produces an output energy that can be many different forms; input energy itself can be in many different forms. When it comes to output energy, we call it an actuator it will produces mechanical energy, it can be kinetic energy, it can be potential energy it can be strain energy, lot of different kind of energies.

It can also be optical energy because producing light is also a form of actuation in the optical domain just as producing a force or displacement is actuation the mechanical domain producing light is an actuation in the optical domain. Similarly, producing radiation is also a type of actuation because when we want to produce radiation of certain kind, we have to release that energy in a controlled fashion.

And if you look at acoustic energy, if I tap on the table, I am using my muscle energy in the form of mechanical energy and that this table takes and produces sound. So, acoustic energy when its released, we have speakers, there are also actuators and we can also use a number of inputs to produce different kinds of fields. They can be electrical fields, magnetic fields all of those are actuations, so output energy can be many different forms.

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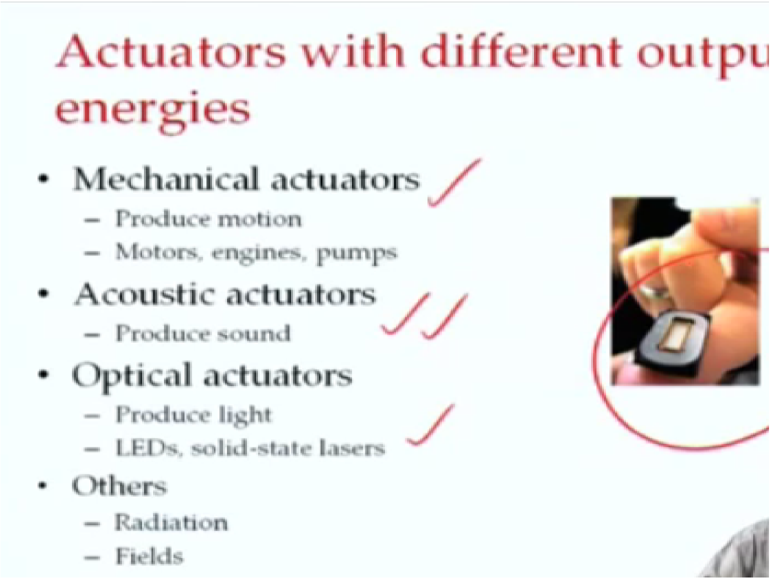

So, actuator need not be defined only has something that moves a body over a distance with some force but can be several other types as we see here. Based on the output energies, we can thus classify actuators as mechanical actuators as we see here. Let us start marking them. We can have mechanical actuators which produce motion, force or torque. There is a motion; it can be a linear motion or angular motion that is why they can be a force or a torque.

Examples of mechanical actuators are motors, engines, pumps because pumps produce pressure, they pressurize a fluid to a higher level than what they are at originally that is also actuation and then we have acoustic actuators, which produce sound, then optical actuators produce light. For example, the light emitting diodes are optical actuators and then there are also solid state lasers which are also optical actuators.

And then similarly, we have radiation producing devices and field producing devices, all of those are actuators. If you look at; why we need to have micro actuators? So far, whatever we have talked about, it is in the context of macro or any size for that matter actuators at any size. But today, we are going to talk about micro actuation so; one can ask why do we need actuators at the small scale; at the micro size?

As we saw in the lecture on micro sensors, we need to move either solids or make the fluids flow for that we need something that moves these; either the solid or fluid for that, we need actuation that is one reason. Other is; today, there is a lot of interest in controlling the motion at the very small sizes and also mechanically characterize a number of things for that also we need actuators.

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And when it comes to acoustic actuation which we see here; this is one of the smallest speakers that are available and these we all use in our consumer products like mobile phone and other things where we need to have very small actuators that is another reason why you want to have; why we want to have very small actuators and let us look at the LEDs; all of us would have seen a number of devices which are very colourful that used in lot of applications.

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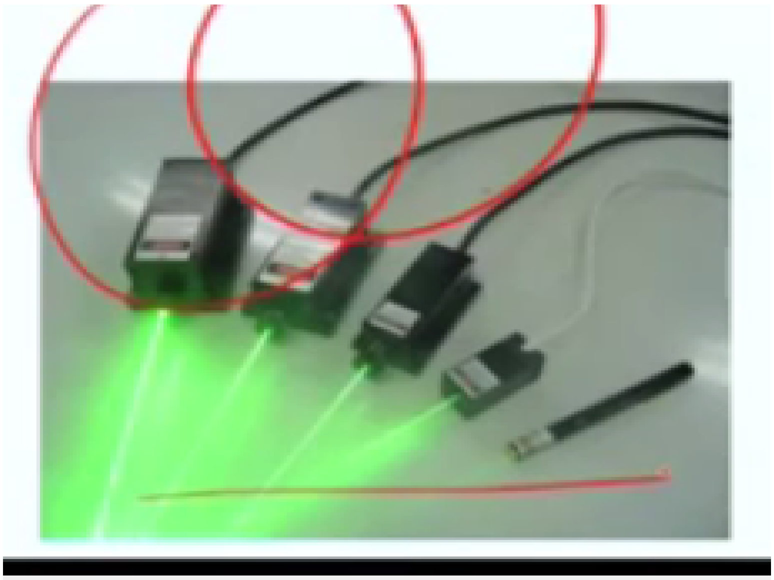

If you ask, whether they are actuators as we just said there are also actuators in the optical domain because they produce light energy by taking electrical energy, so they fit the definition of an actuator. Here, we have shown solid state lasers; a laser pointer that you use is also an actuator because that is also producing light. So, we have actuators in different domains not just in mechanical domain all of these are important at the micro scale.

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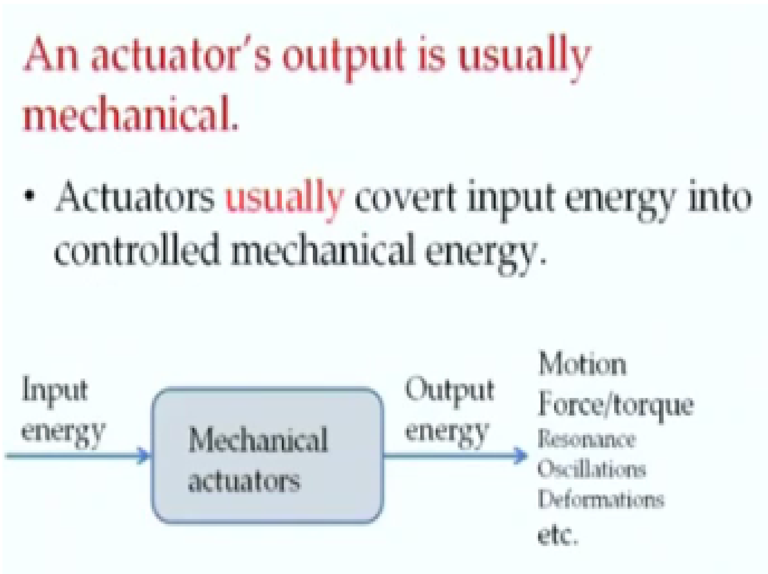

If you take a mechanical actuator, then the output energy is going to be only mechanical, so there will have motion and producing some force or torque. So, in that sense this is a subset of the actuators. We can also wish that a particular element is resonating that is; it is vibrating at certain frequency that you want, then that is also a type of actuation and many sensors require this kind of resonant motion.

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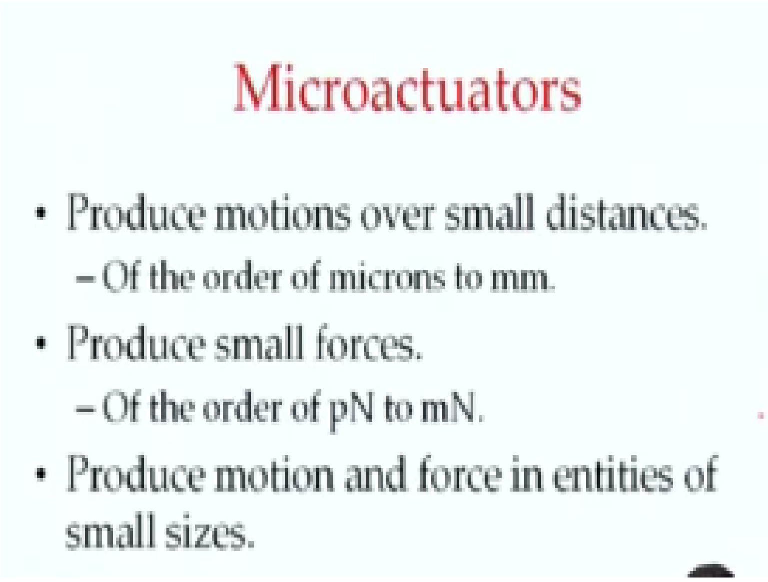

And you may want to keep certain thing oscillating, for example; if you want to produce a mechanical clock, you need that so, that also is a type of mechanical actuation and you may want to deform a body that is also a mechanical actuation. In fact, all of these will go into this that is a type of motion that you want produce with certain force and certain torque. If, you say again how do you distinguish between an actuator at the macro size as well as the micros size?

Then we have to have some criteria, we can just say that if the motion produced is over a very small distance; let us say the order of microns to maybe a millimetre, then we can call it a micro actuator or the force produced is very small of the order of Pico newtons to millinewtons precisely they produce that much of force then also we can call them micro actuators. If the actuator itself is very small, then also we can call it a macro actuator even it produces large force or large displacement.

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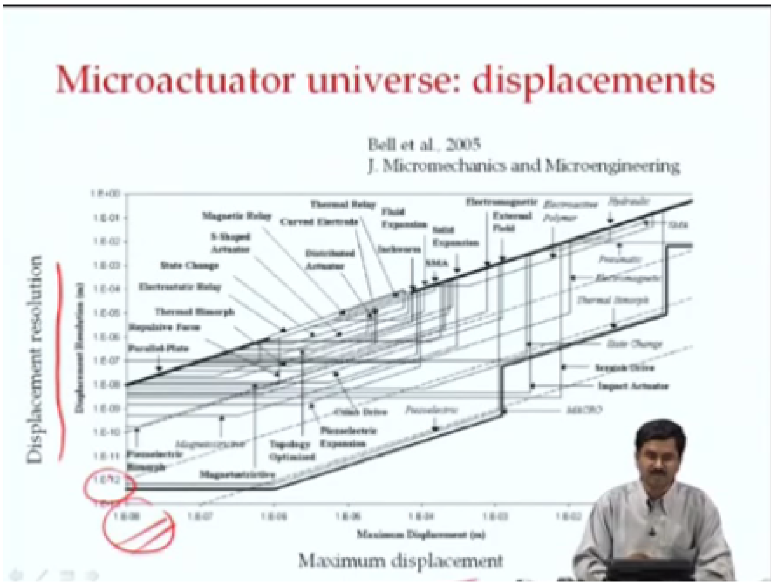

So, the size is small then also we can call it a micro actuator. Let us look at various actuators that are available. The title of this slide says that we are looking at the universe of micro actuators, it is not the complete universe but majority of the actuators are shown in this one graph. On the y axis, we have displacement resolution of various actuators; on the x axis, we have maximum displacement that these actuators can generate.

And all different types of actuators it may be too hard to read everything here but what it shows is that; we can have displacement up to 0.1 meters with micro actuator that is 100 centimetres, so that is not really small in size but compared to macro actuators, it can be considered small. It can go down as much as 10 nanometres that is even smaller than that is also possible because this graph can actually extend further more than 10 nanometres that is shown here.

And then resolution also can go to very small values, in fact what this shows here is 10 power -12 meters and that is Pico meters 10 power -12 meters, you can have a resolution that is actuator moves such fine distances at our command, so micro actuators have very high resolution than anything that we know at the macro scale and they can also produce the same time quite a large amount of activation.

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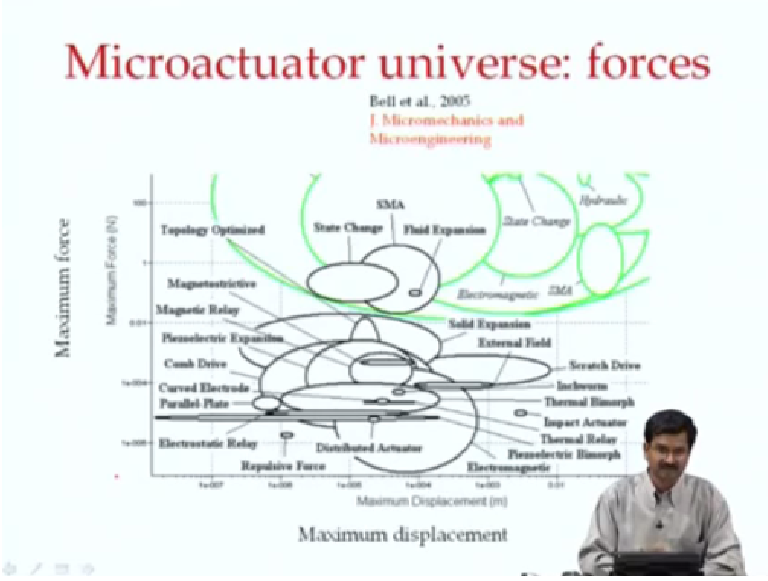

Let us look at the same micro universe in terms of the forces because the previous slide, we saw how displacements were. Now, if you look at force that these actuators are able to produce, this shows that we can go several orders of magnitude from; let us say fraction of a Newton which could be a Pico Newton all the way to 100s of newtons but 100s of Newton producing actuators may not be very small, they will be very large.

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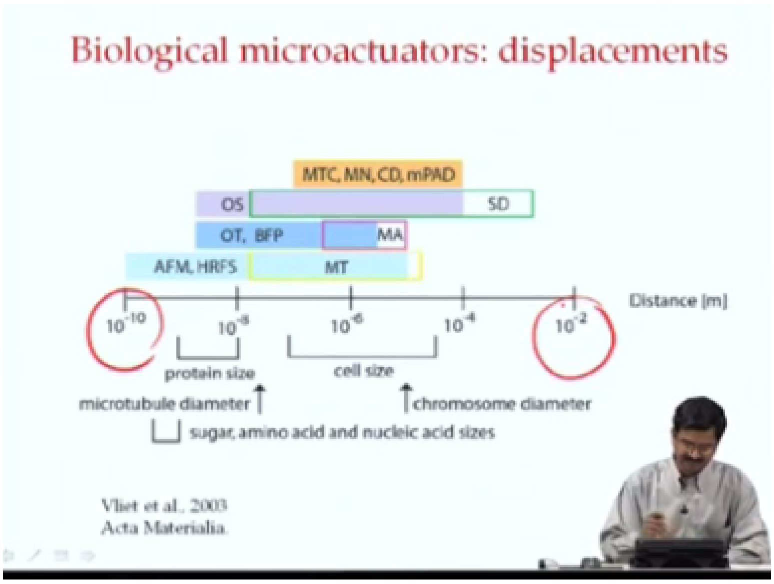

But one thing that micro actuators help us do; is to use several of them as an array in order to produce large force, if you put all the actuators in parallel you get large force. If you look at micro actuators that are there in the biological world that is the living organisms, they can do a number of things all that is possible because of actuators. If you look at displacements, you can go from as much as an angstrom which is 10 power -10 meters to a centimetre or even larger.

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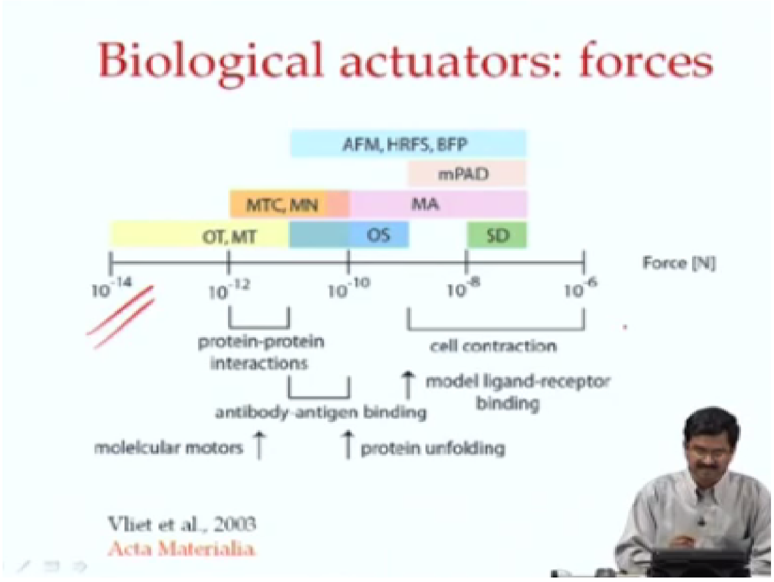

Because we can move over large distances and there are today actuators that can produce this kind of displacement and also if you look at the forces that biological world has; again it can go from very small values that is 100th of the Pico Newton 10 power -14 Newtons to about a micro newton. Now, we are saying these are biological actuators where they produce this kind of forces.

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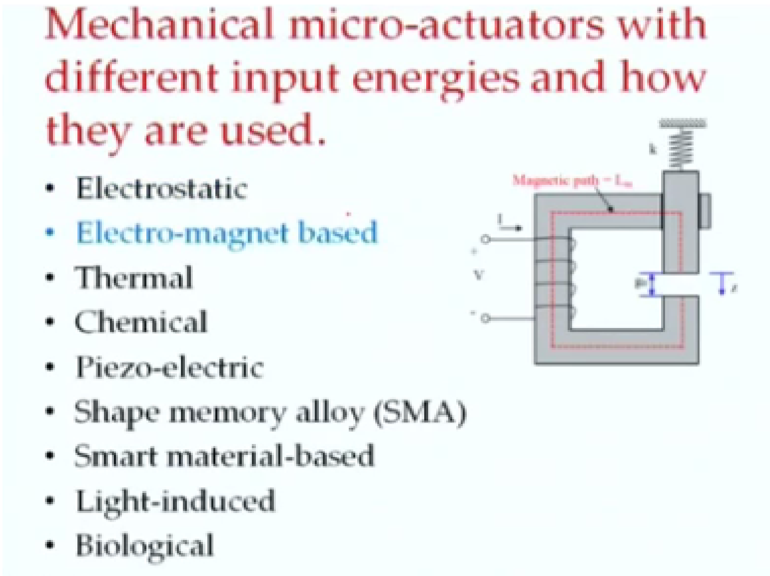

But now, there are also engineered device that is where we have the micro actuators which can interact with things of that scale. If there is a biological actuator that produces a micro newton, then we can measure that that will be called then a sensor but we can match that force and try to manipulate things at very small scales. If you look at mechanical actuators then we have lot of different varieties and they are different based on the type of input energy that they use.

First, we have electrostatic; electrostatic actuation is a very simple actuation technique at the micro scale. In order to see how it works; we just have to consider a very simple model of a parallel plate capacitor. Parallel plate capacitor is a very simple model, if you just look at 2 plates that are parallel to each other there is a plate at the top at the bottom; let us say that I misalign one of them, so you can see the plates they both have the same cross section.

They do not need to have but if they have and I displaced one of them this way when I apply voltage between these 2 electrostatic force tries to align them, so that becomes an actuation or if I displace in this way, it will move this way and if I; if they are together, if I separate them out by applying a certain electrostatic force, then the force will try to attract them back. If I separate them by mechanical means, it will try to attract them back that becomes an actuator.

So, with electrostatic actuation with a very simple geometry, we can get actuation. We also have electric magnet based actuators that is again a notion that is familiar to many, where we have a coil through which we pass some current that creates a magnetic field and if you have an armature and there is a magnetic path for it, it will try to close the gap in this particular figure when I pass current here because of magnetic field generated this particular sliding element will try to move down along the magnetic path, then we get a magnetic actuation.

This is also widely used and we will see how it would work when you try to miniaturize. We also have thermal actuation; thermal actuation can be of again very different kinds. One kind is; you just take a piece of material and heat it, all materials when they are heated or most materials when they are heated, they will expand. When they expand if you try to prevent that expansion that becomes an actuation.

Because certain thing, let us say we have this plate here and we heat it and that would expand, if I hold it, so that I do not; I do not allow it to expand, then I would feel a force that is thermal actuation. Thermal actuation is a huge force because we know that bridges; large bridges might develop cracks and even collapse based on thermal expansion. If you do not let it to expand the way it wants to, then it can have a problem.

If we look at thermal actuation micro scale, we find that much larger force is obtained as compared with electrostatic actuation or electro magnet based actuation. Chemical actuation another important one, if you look at our IC engines internal combustion engines, one can say this is a chemical actuator because there is a combustion taking place which is a chemical reaction and that is producing energy.

Similarly, one can have micro combustors; we can make micro rockets and produce actuator the small scale using chemical energy. We also have here something called piezoelectric; piezoelectric material is a special kind of material that produces electric charge when it is subject to some mechanical strain and likewise when you supply it some electric charge then will produce mechanical strain.

Meaning that; it will deform and produce force and motion, such piezoelectric actuators can also be used micro scales and they are indeed used even in some commercial micro actuators that we can buy and use today. We have another kind of special material called shape memory alloy material and let us watch a small movie in order to understand what this shape memory alloy material is.

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So, here we have the; we see a spring that looks like a normal spring here but upon heating we see that; let us play this movie one more time; let us play this movie one more time, to see that by just heating we can make this spring that is there, the moment it is heated it is changing shape it is called shape memory alloy material because it remembers its shape upon heating. It is a special kind of material which undergoes a phase transformation so that it can go back to a shape that you made it to remember.

If you want to use such an actuator, such a material as an actuator you have to constrain it because otherwise it will move or the way it wants to but here the same spring if we take; let us play this movie again the same spring it is in expanded form when you heat it, it is contracting. If you give it a load, it will try to pull the load along with it because it wants to go back to its memorized shape.

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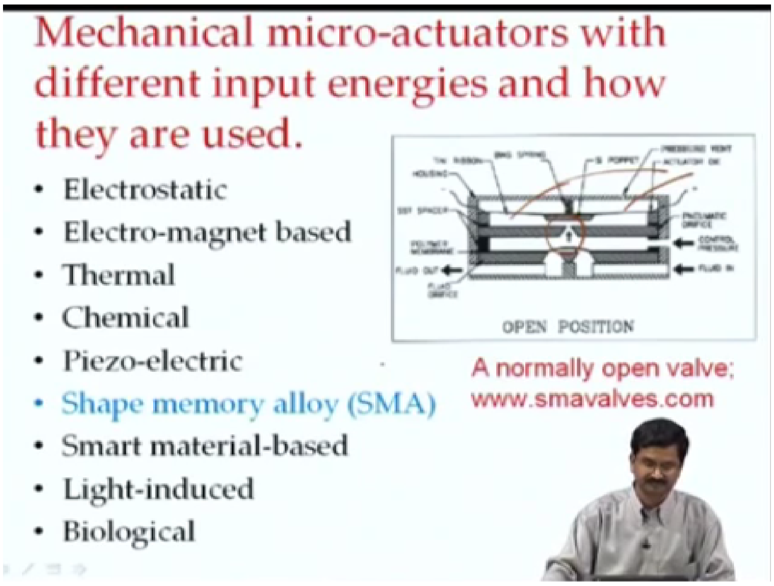

So, if we take a spring like this, if I were to attach a load here then it would try to move that load and that is how this actuation works. So, we can use the shape memory alloy materials also for the purpose of activation. There are also a number of other active materials which are called smart materials which are used to produce a number of different types of actuators. You can also use these actuators to make a number of devices where actuation is needed.

Here, we are showing a valve, it is a normally open valve where there is a market. We have this portion; these 2 beams, beam like things that we see are made of shape memory alloy material they are more like ribbons, small strips of material. When you heat it as we saw in the case of a spring; that will try to return to its memorized shape which will make this valve move down here and close this orifice, so it acts like an actuator.

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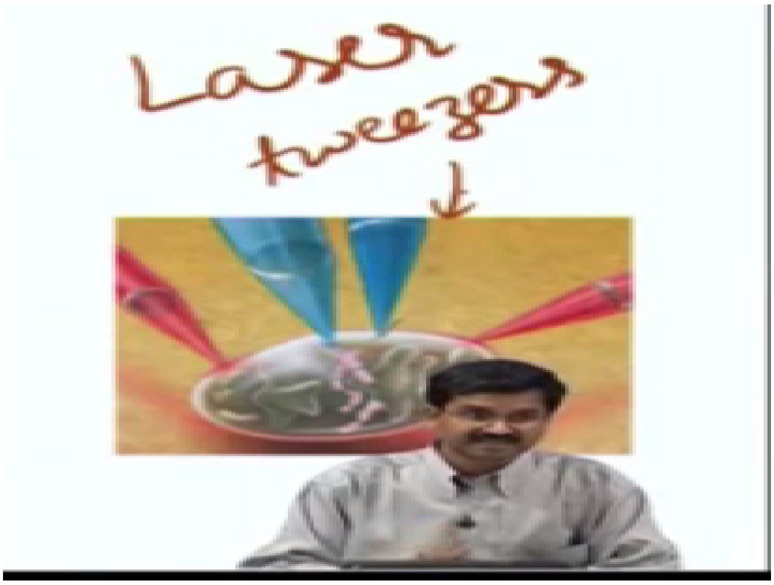

So, we can use these actuators in micro application, the whole thing here the valve can be a micro valve; very small valve. We can also use light energy to produce mechanical motion. We talked about optical actuators we are producing light itself is considered actuation but we can use lasers as it is shown here to produce mechanical force this is artist rendering but what are called laser tweezers, so you can use lasers and make tweezers.

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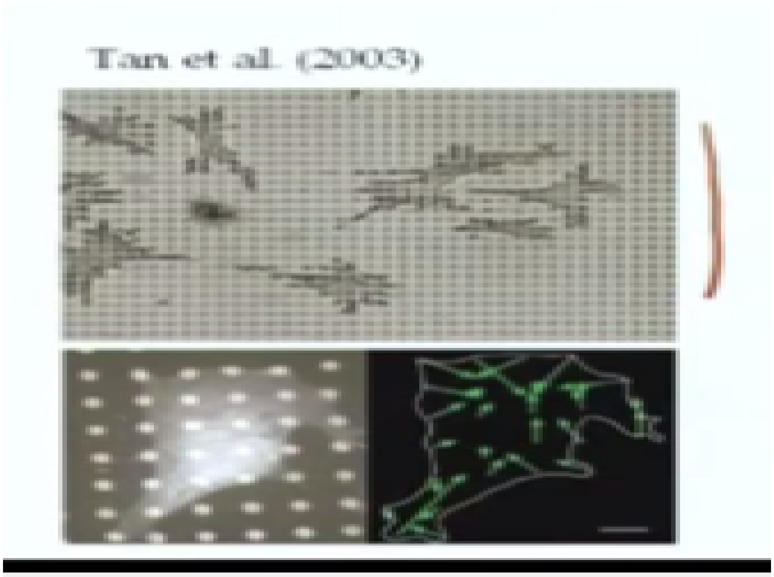

With the laser tweezers, you can hold small biological cells which can be only a few microns in diameter or any other sizes that we look at our fibres and hold it with light energy. We also have lot of biological actuators which are using the way biological world moves itself at the small scales. So, what we see in this picture over here; is a number of posts, imagine that we are looking at the top view of a region which has lot of posts.

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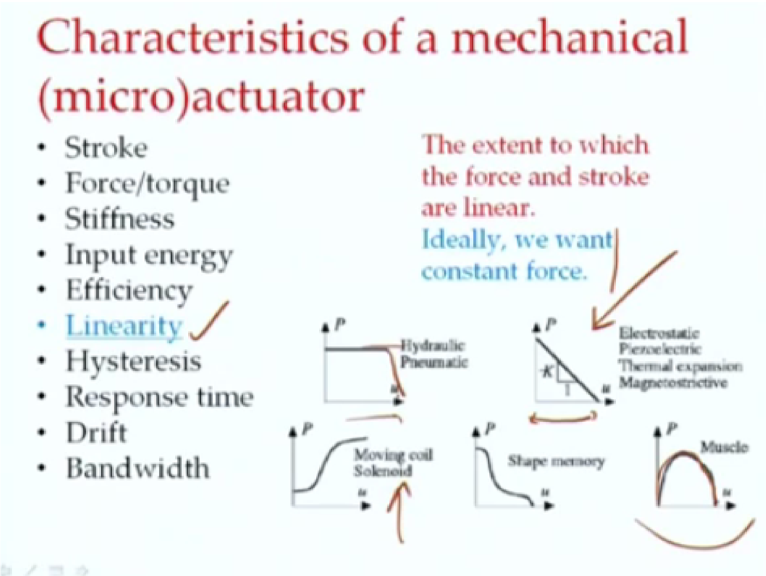

And if you release a cell here, that cell migrates from one side to the other side using its own energy and its own activation, one can today tap such biological actuation and use it for our purposes, there are biological rotary motors that one can use and produce a meaningful mechanical work. Let us look at now certain characteristics of actuators in general because they apply to micro actuators also.

The first thing is stroke; every actuator will have a stroke, it is a maximum displacement that is possible with that actuator. The force and torque this is maximum force or torque generated by an actuator one has to know, when you are going to choose an actuator for a purpose, you want to know how much force or torque that can generate. One thing that we need to remember in addition to stroke and force or torque, we also need to look at the stiffness of an actuator.

Many actuators have their own stiffness, meaning that they usually will not be able to produce the same force or the entire stroke. Initially, they will have large force as the displacement increases the actuating force, that the force that is generated or that the one that you can use keeps decreasing that we attribute to the stiffness of the actuator. So, rate at which the actuator force or torque decrease it with stroke is referred to as the stiffness of the actuator.

And the input energy, so most actuators that we use; usually use either voltage or current in order or electrical energy as the input, there are exceptions but many of the things we see have electrical energy supplied to them, so you have to know whether the actuator requires only 5 volts or 500 volts, so that is also something we need to remember. This also leads us to another term that we need to worry about which is efficiency that is the ratio; ratio of the released energy to the input energy and that we ideally want it to be 100% or ratio to be 1.

But that usually not the case, every actuator delivers output energy which is usually less than the input energy because in the process, because of stiffness it has its own dissipation, so efficiency are not going to be 100%. One more very important concept is linearity. Sensors we said need to have linearity or a large range whereas when it comes to actuators, most of them are linear, the shape memory material that we just saw or piezoelectric material.

And other things; electrostatic and other forces they need to be ideally speaking like hydraulic and pneumatic with the stroke with the displacement we would like to have the force to be constant but it is not, if force drops down because their stiffness is linear, so the force will drop down and there will be a maximum stroke beyond which they cannot produce any more force because the force is already 0.

P here refers to the force or torque that they are going to generate but if you look at magnetic the moving coil solenoid, it has a nonlinear force displacement characteristic. Similarly, the shape memory material that we saw it has a nonlinear force displacement characteristic and or muscle which we can call the biological actuator which has even more funnier force difficult characteristic, it starts with 0 force at 0 zero displacement goes to a maximum value and comes down.

It may vary but what it shows is a different way of producing the force and displacement but you can see in all the actuators, there is a certain stroke beyond that they cannot provide. At that stroke, they produce actually 0 force, so we have to even though ideally would like to have constant force which hydraulic and pneumatic actuations can provide over a sufficiently large displacement, after that they also taper off like this that is they also do not have infinite stroke.

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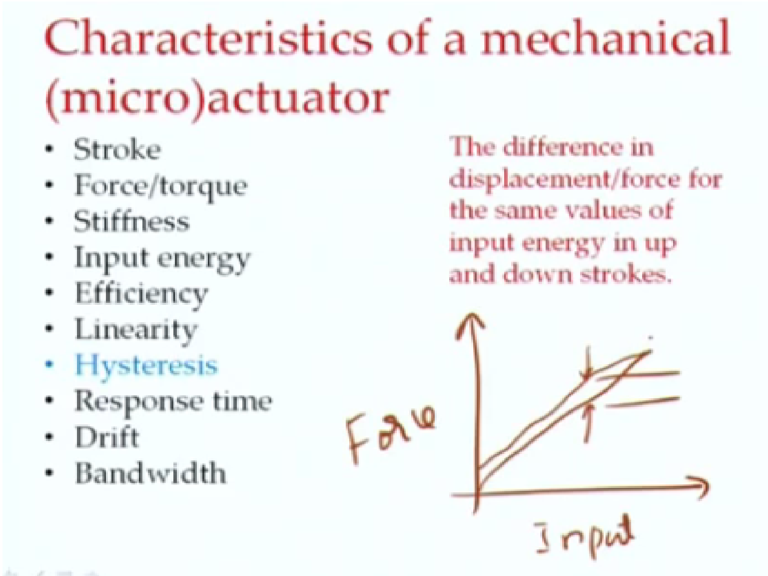

But this something we need to remember when we use them at macro scale or micro scale. Another thing is that, like sensors actuators also have their own hysteresis, if I were to say that there is input energy which can be either voltage or current. If I want to say, i want to have certain force while slowly increasing the input energy, it may just go like this but then when I start decreasing the input energy, let us I turn down my voltage, it would not usually follow the same path.

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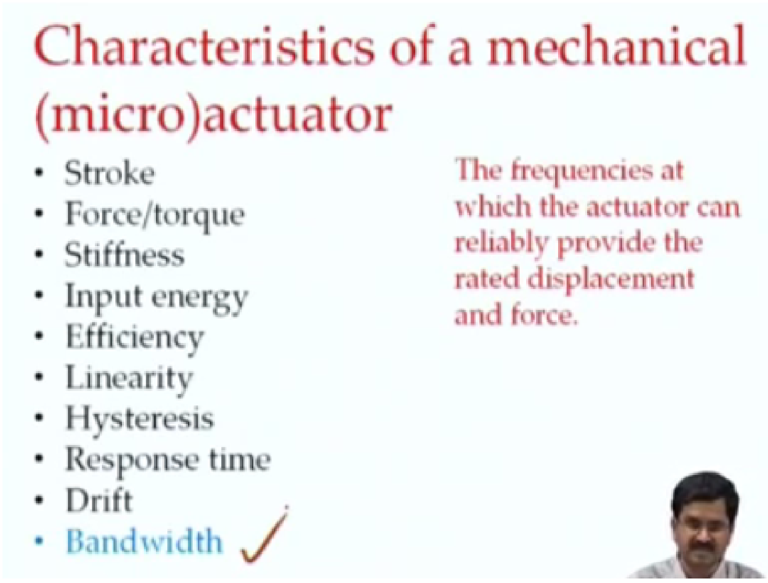

There will be a certain difference while coming back and if there is such a difference, we call that cap as hysteresis which is there in sensors, which is also there in actuators and the response time is the time taken by the actuator to respond to the signal that we have given. We give a command to say that the actuator has to move but will not move instantly, it will need some time.

And that time is the response time ideally, we want this to be as low as possible, so that it is instantaneous, it is like turning on the switch and the light bulb blow glows. Similarly, we would like to have the moment the signal is given, we want actuated to move. The drift, which is the unintended shift in force or displacement even with the input energy kept at a steady level at a constant value.

It can happen if you want to hold a certain object with certain force, if you give that same energy after a while it may not actually produce that force, it may be more it may be less, usually it will be less and that is drifting. It can happen not only with the force but also with displacement. These are usually indicators of not so good actuator, their imperfections. If a good actuator is there, then it will not suffer from the drift problem.

But they will always be a drift that we can neglect because it is very small. The last thing is bandwidth that is actuators should produce the force that you want and take it back to 0 and then come back to the force like I want to oscillate a body, I will have to apply force and remove the force, apply force and remove the force. I want to do that a very fast rate that is contained in the term bandwidth.

So, at what frequencies the actuator can produce the force that you want? If you take a thermal actuator where I heat it and I would like it to deform and produce the force and then after some time, I would like to make it deform produce the force again. Before that, I have to heat it and then cool it; both heating and cooling take time and that decides the rate at which I can use this actuator repeatedly.

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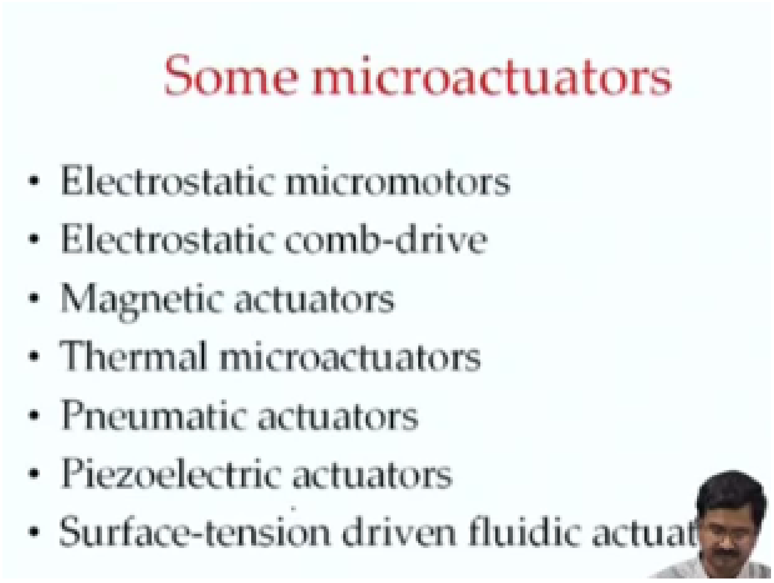

So, bandwidth is also an important characteristic of an actuator. Let us look at a few types of micro actuators having discussed the general characteristics of micro actuators. We will focus on electrostatic actuators first.

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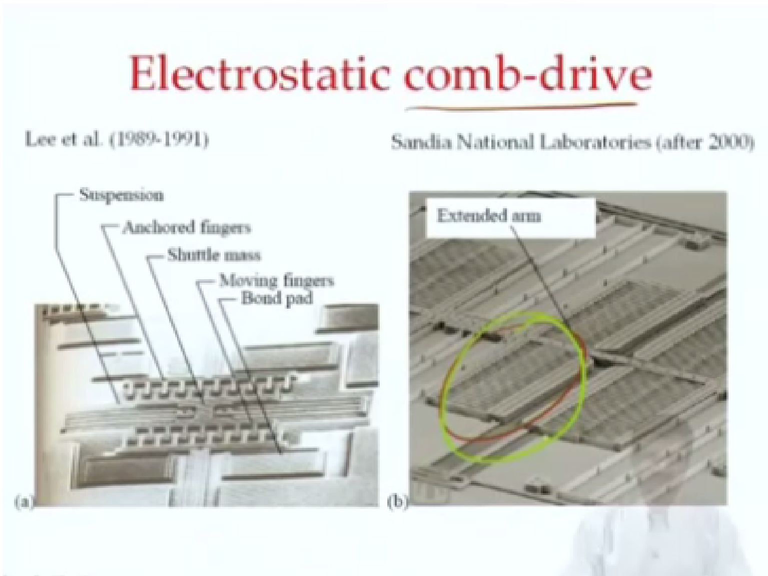

Here is an electrostatic actuator which is called a comb drive because it has an element that looks like a comb. If you look at the element here; let us use a different colour, if you look at this portion here which looks like a comb because it has fingers that a comb has; one set will be fixed, other set will be moving just like we saw with this parallel plate capacitor where one is moving this way while other is fixed.

And if I have an array of these that becomes a comb drive, they are interdigitated fingers each of which forms a parallel plate capacitor when apply voltage between them, they try to align and produce the motion and if you put a load there also against the load they can move and still produce the force. So, this is one can say the; is the workhorse in the micro domain that is the actuator that is used most widely in the micro domain is this electrostatic comb drive.

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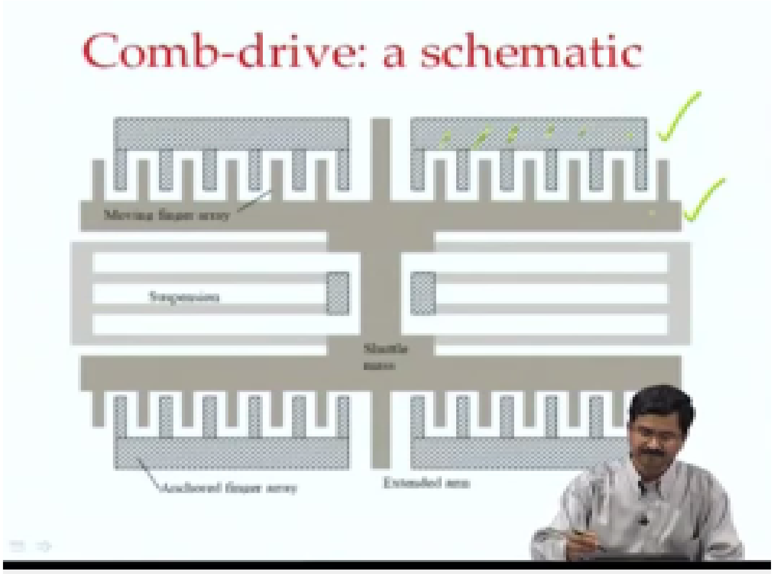

The one you see on the left here is an actual that was made in the late 1980s and today this is a regular feature on many research labs activities as well as in commercial devices and many types of sensors. This is the schematic of what we just saw, so you have what looks like a comb with fingers that can move and then we have the other one where the other set of comb fingers which are hatched here which are stationary that is they do not move.

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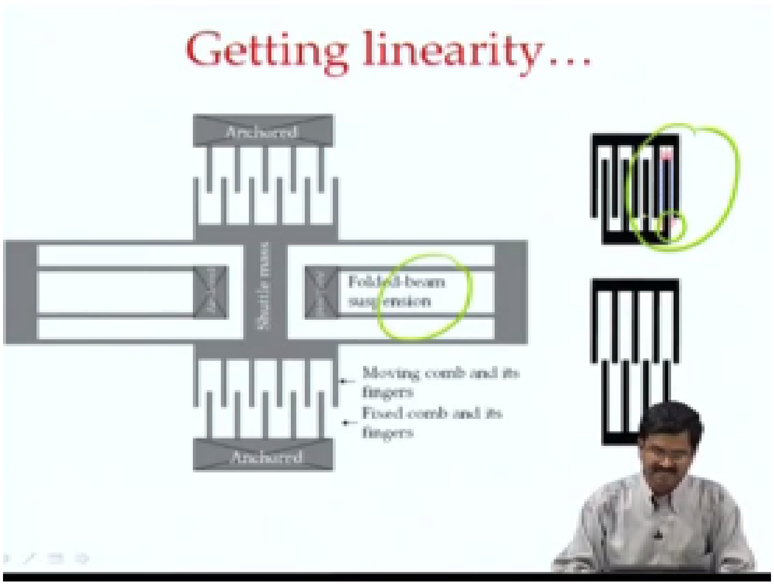

When apply voltage between this and this moving body we will get the motion and also the force. If you look at this picture here, would shows an electric field that is there between these 2 plates and at the corners, there will be something called fringing fields as opposed to having electric field that is uniform between the 2 plates or the edges will have this fringing fields which actually helps in making these actuators move with more force.

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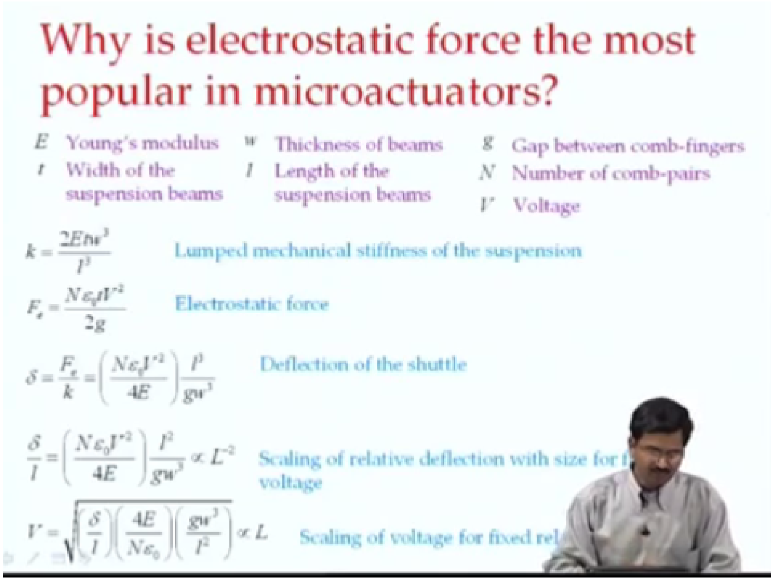

But fringing can also cause non linearity in these actuators and non linearity might come from the beams that support the shuttle mass but also from the electrostatics. So, making an actuator linear is an important aspect in terms of usage of that. If you ask the question, why electrostatic force is the most popular in micro actuators? We can do a simple calculation as it is shown here.

We look at the force that the electrostatic actuator can produce and that is given by the formula here. We have N, where is a number of comb fingers epsilon0 is a permittivity of free space and t is a height or thickness of the comb finger and the V is the voltage that we are applying divided by 2g that we have and this g refers to the gap between the 2 plates that we have here in this case and these are force that this actuator produces.

And how much it deforms depends on the stiffness of the suspension which we are denoting by k, which is a spring constant which is a function of the material properties Young's modulus as well as Poisson ratio and the geometry of the actuator, the height of the cone fingers, the width of the cone fingers and the length of the suspension beams, so depends on the thickness not in the cone fingers but also the thickness of the suspension beams and width of the suspension beams and length of the suspension beams, we have a formula for the stiffness.

So, if you say how much deflection it is going to generate we take force and divided by the stiffness and if you just take one of the l here, to see relative deflection that is we are looking at now, why is electrostatic force very popular at micro scale as opposed to macro scale? We hardly use electrostatic actuation that is the scale at which we live in; we do not use electrostatic motors.

Whereas, at micro scale it is very popular, in order to see that we take this relative deflection, if I have an actuator of certain size relative to its size, how much does it deform? It turns out that that ratio the displacement divided by the size of the actuator is proportional to or inversely proportional to the square of the size, so as a size decreases we get larger and larger force and another way of looking at this is, if I want a certain delta/l that is the fraction of the distance compared to its size.

Let us say I want it to be 10% or 0.1 the ratio, then how much voltage do I need? That is proportional to the size of the device. If I want 10% of actuation from a micro actuator, if I am using 1volt, the same actuator if I make it at a large scale it would require 1 million volts. If I what I have 100 or 10 microns, if I make it 10 meter, they would be million volts, so does not scale very well when we consider it at the macro scale but micro scale it is very attractive.

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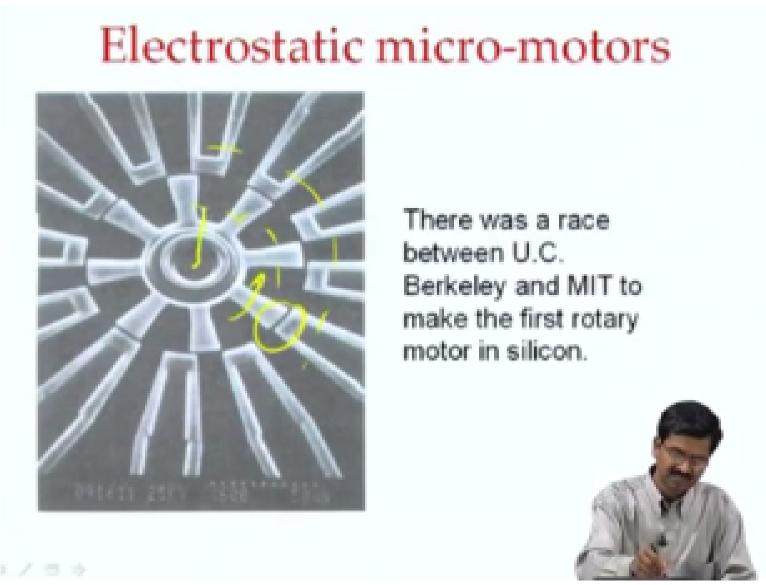

And in fact, the first electrostatic actuators were built in late 1980s around 1986, 87 times and there was actually a race between 2 universities in America where they wanted to produce the first electrostatic micro motor which you see here. We have the stator poles here, these are all the stators and there are; see these are the rotor poles and then there are stator poles on the side.

If we look at one of these here, that is also like a parallel plate capacitor. When we apply, when we hold one of them fixed and apply voltage between them they try to align, so here you can see that there is a small misalignment between the 2 and when apply force, it will try to align and in the process will make this rotor rotate and we are looking at the top view here, so the rotor will start spinning about this axis.

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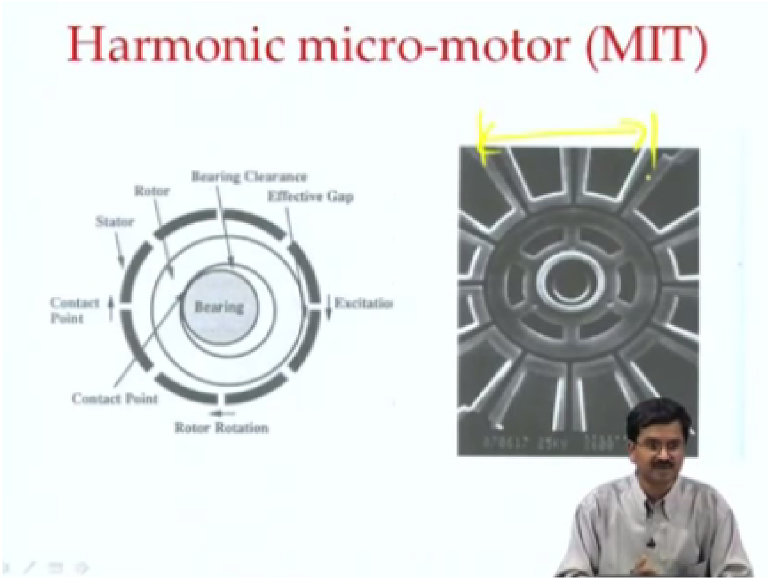

And there are different configurations of these motors, there is something called a harmonic micro motor that was also made around 1988, 1990 time where these actuators were shown for the first time that you can have things rotate at your command at the micro scale and they involve my new joints to be made and force applied and one can make them rotate at a very high speed of the order of 10s of 1000s of RPM revolutions per minute.

Imagine the micro actuator that is only about; let us say 500 microns in diameter, let us say this distance is half a millimetre, such a small micro motor can spin at very high speeds. This electronic actuator does not produce a large torque for us to do anything useful but it can be used in a number of sensors where we just need to move something in order to sense a particular quantity.

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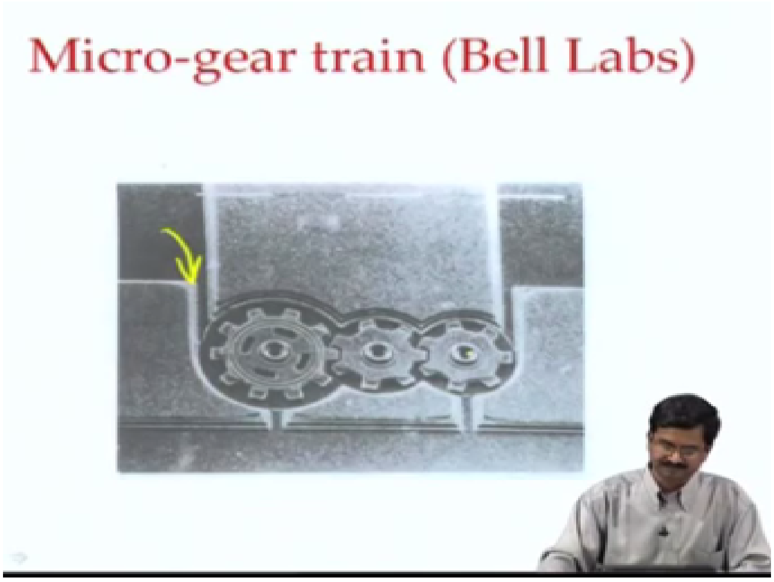

Here a pump was made at Bell Laboratories again in late 1980s to early 90s where with the help of a fluid going in could be a compressed air or liquid where it will turn and produce the motion and then you can put an induction motor on top of that and try to produce electrical energy also with pneumatic but this was micro gear train come an actuator.

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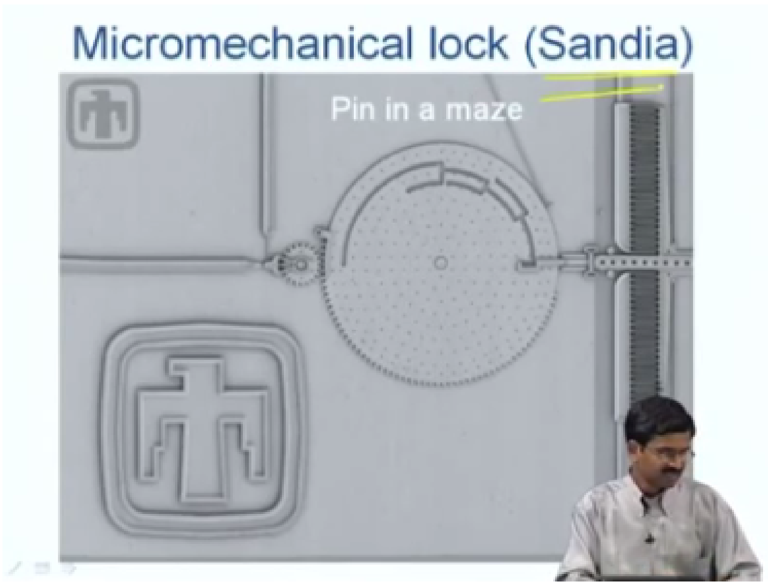

And people have made micro engines; this micro engine that you are seeing is made in the Sandia National Laboratories, I have a small chip that shows this engine.

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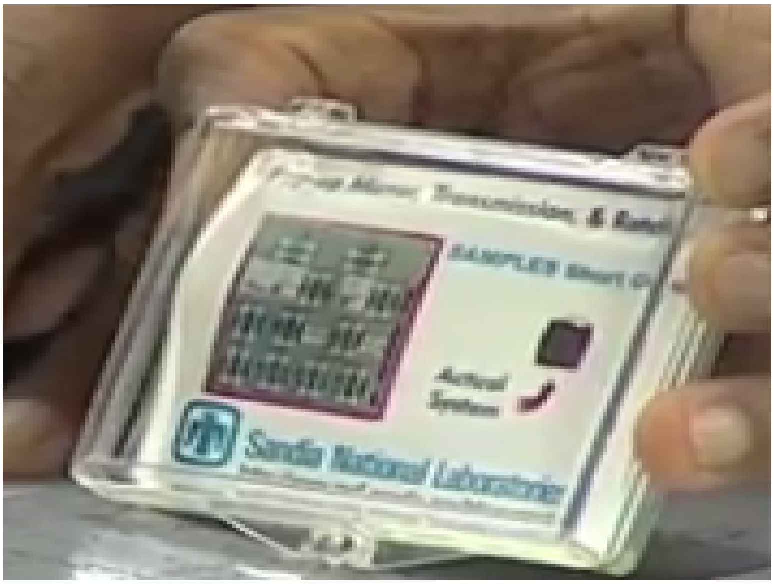

So, this chip as you can see over here the chip is less than a centimetre by centimetre square and that can produce a number of gears that rotate at very high speeds and this is the drawing of what are all inside.

One of them you are seeing it on the screen now which is there is a motion that is goes up and down here and also this goes back and forth left and right this way that turns a small pinion that turns a gear, this motion which is like a comb drive similar to what we already have discussed and that is configured in a way that will make a rotary thing go around on round and that happens at a very high speed such as millions of RPM.

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You can use gear trains to reduce them and that will increase the target it can generate and you can use them for certain purposes mostly instances because the torque produced is really not very high. This is the close up view of this actuator and here you see a gear train that was placed given by this micro engine.

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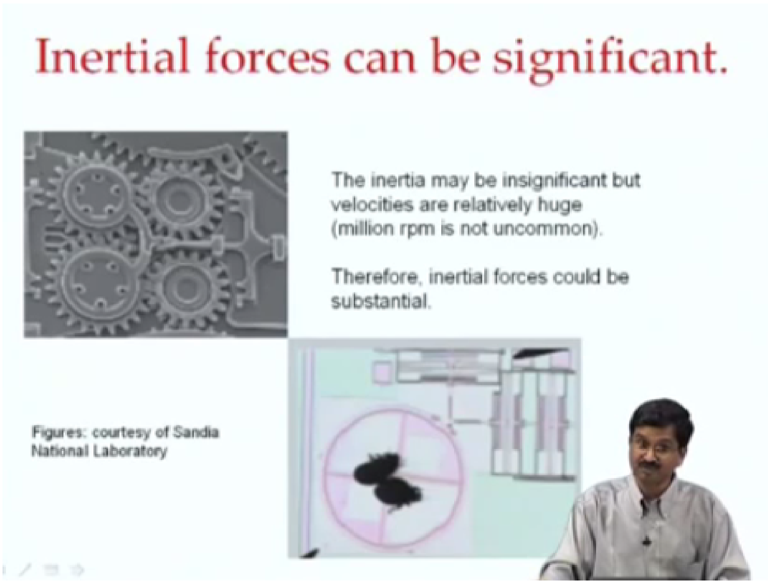

And you see here a more complicated gear train; a number of useful mechanical things can be done using these micro actuators which are electrostatic actuators.

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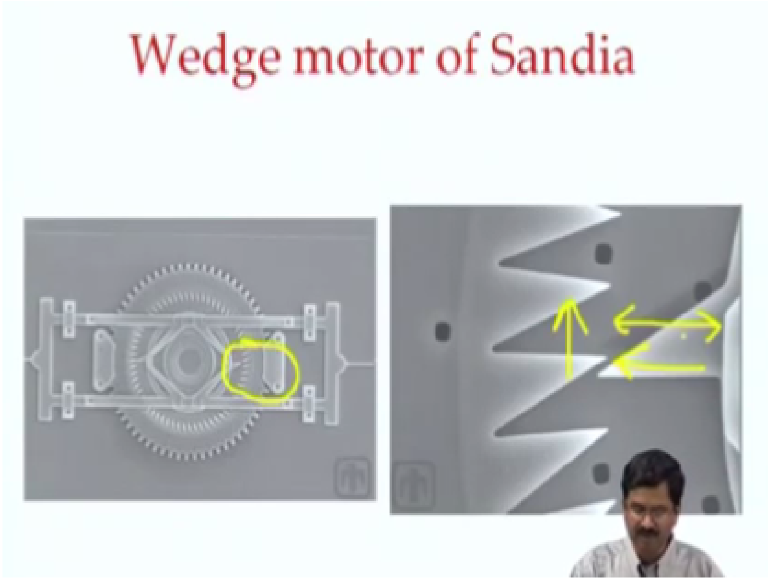

This is a another kind of motor which is a wedge motor where the reciprocating motion back and forth motion makes a gear underneath that rotate and if you look at the close up view of a small region over here which is shown on the figure on the right side, as we move this back and forth, imagine that this particular device is moved back and forth and you can imagine that when I am moving it to the left this way.

That is; I move this in this direction then this wedge motion between them makes this move up in this direction. So, if I do that and bring back then nothing happens because out of contact with this and then again when you move this would have advanced and will again move up, so this is the portion that we see this tangential force will make it rotate, one can make a wedge motor and the motion of this is obtained using the electrostatic comb drive that is why comb drive is said to be the workhorse of micro actuation.

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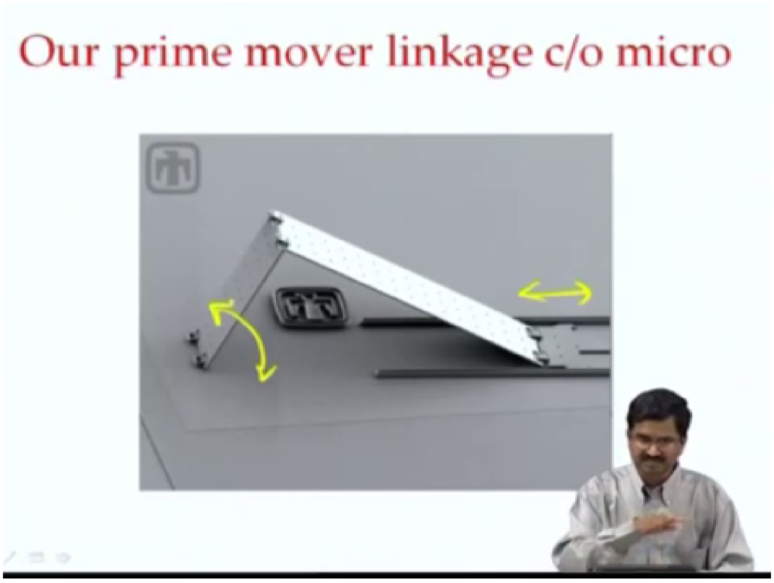

You can also have promotion produced with a comb drive attached at this end, going back and forth, you can make this rotate up and down perpend to the silicon wafer.

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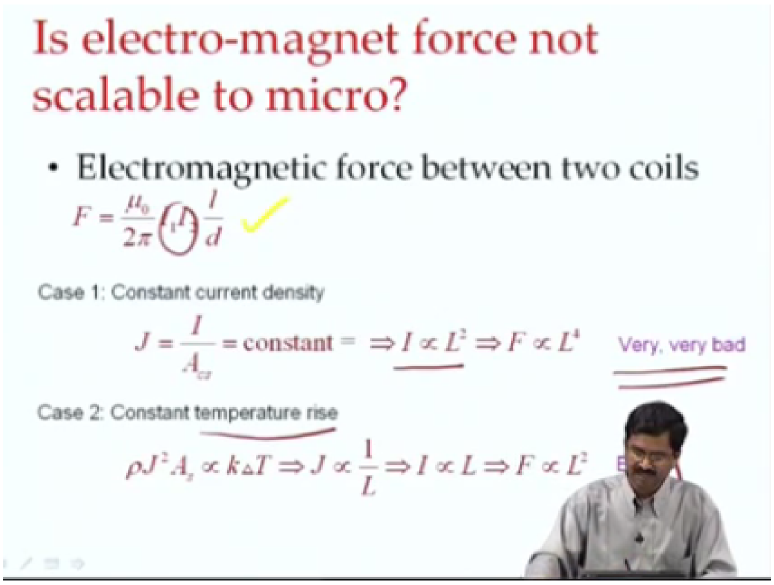

If you ask the question is electro magnet forces is scalable favourably or not to the micro domain, then let us look at it from a very simple viewpoint. Biot savart law tells us that the force between 2 current carrying conductors is given as the product of the 2 currents with l, indicating the length of the current carrying conductor and d, the gap between them; it is proportional to I1 and I2.

If we keep the current density constant, then we will find that the current is proportional to the size square. Since, we have 2 currents here in the force is proportional to the size to the 4th and when we miniaturize it, it turns out to be very, very bad because we get very little force. If you use some other criterion saying that current carrying conductor usually get hot and if you say we want to have for the same temperature rise, how does it behave?

Then we will find that the force is now proportional to l square as opposed to l to the 4 which is still bad because if I look at something that produces electric magnetic motion of sizable force or displacement, when it comes to the micro scale, we get millionth or 10 power -12 factor which is very, very small and that will not help us much to have magnetic actuation.

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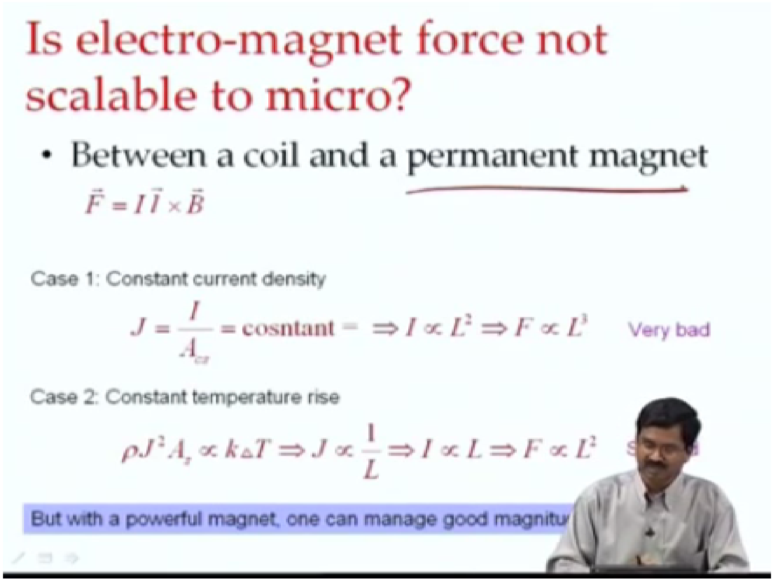

But then, we can use a different technique by using a permanent magnet. If you take a magnet which has certain magnetic field very close to it, it is going to have very high magnetic field there are some rare earth magnets which have magnetic field of the order of 1 Tesla, 2 Tesla, so if you use those very powerful small magnets and very close to them we have a very small very high magnetic field.

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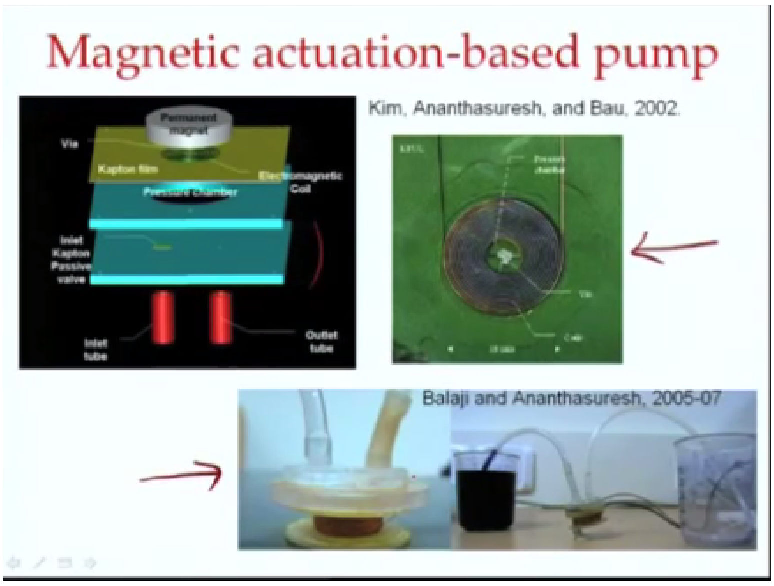

Then you can get large magnetic force in which case we can make electromagnetic based force also useful to produce actuation. So, here is a pump that you see which is based on electro magnet actuation. This is a schematic that we see here and this is just a photograph of the coil which is made in the form of a planar spiral coil and that is wound here and there is a small membrane that makes this membrane.

This is actuated by the changing current that is there in the coil and then changing magnetic field with the presence of magnetic permanent magnet produced field and that will make this membrane go up and down and if you put in Inlet and outlet valve, you can make liquid go in and come out. This actuator is actually not very small, this is a wristwatch sized actuator but one can use the same principle to produce an actuator at the micro scale as well.

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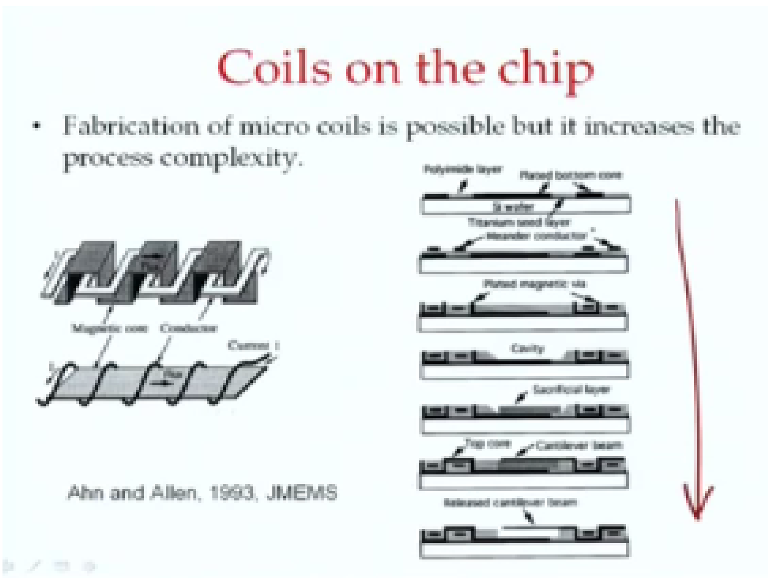

And you can also have coils at the very small scales, as you can imagine it will be very difficult to wind a coil at the small sizes because you would need sophisticated assembly techniques to wind a coil whereas you can have a surface micromachining process which is the process flow that is shown here, you start a silicon wafer and deposit a layer and remove. If you follow certain steps, you can get an equivalent of a coil but it has a different geometric form as shown here.

But effectively, there is a core around which a coil is wound, it is not going to look like taking a rod and winding a coil but topologically, it is equivalent and when you pass current through it because of the core it produces high magnetic field, so you can actually have in addition to using rare earth permanent magnets, you can have magnetic field produced by passing current, you can have a truly electro magnet based actuation.

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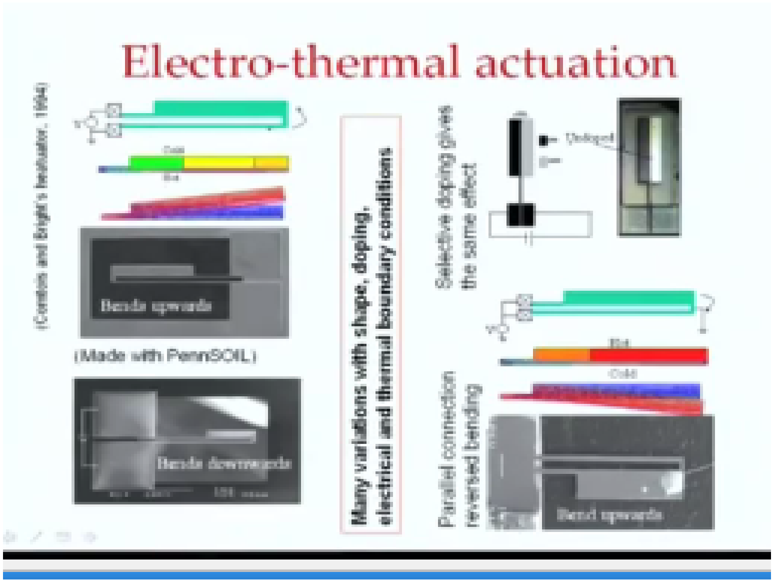

Electro thermal actuation usually, we can have 2 materials that have different thermal expansion coefficient. If we have those, when you heat them, one material wants to expand more than the other but then they are stuck together, let us say we take these 2 plates and the red one has certain thermal expansion coefficient, this grey colour one has another thermal expansion coefficient I join them together and hold it at one end and heat it.

Because let us, assume that red one wants to expand more than the white one but they cannot because they are joined together. The only way they can happen they can still produce a expansion that they intrinsically have is by bending if I have these are stiff plate, so I cannot bend them. If I take these 2; let us say the top one expands more than the bottom one the way, it can achieve equilibrium is to bend like this.

When it bends, we have larger length on the top side compared to the bottom side and that is how you can produce actuation and coming back to the slide here where we can achieve this differential expansion not only with 2 different materials that have different thermal expansion coefficient, we can vary the width. We have a large width here, the small width when you pass current through it the one that is small, will have larger current density, it will get harder as the red one is shown here.

Whereas the top one will be relatively cold and this will expand more than the other, so it will bend like this as shown in this figure over here okay. This is a silicon electro thermal actuator those made and this can move and we can put it in different configurations and also play with the doping which is adding impurities to silicon, then also you can change the current density that is there in these actuators and produce different types of motions that you want.

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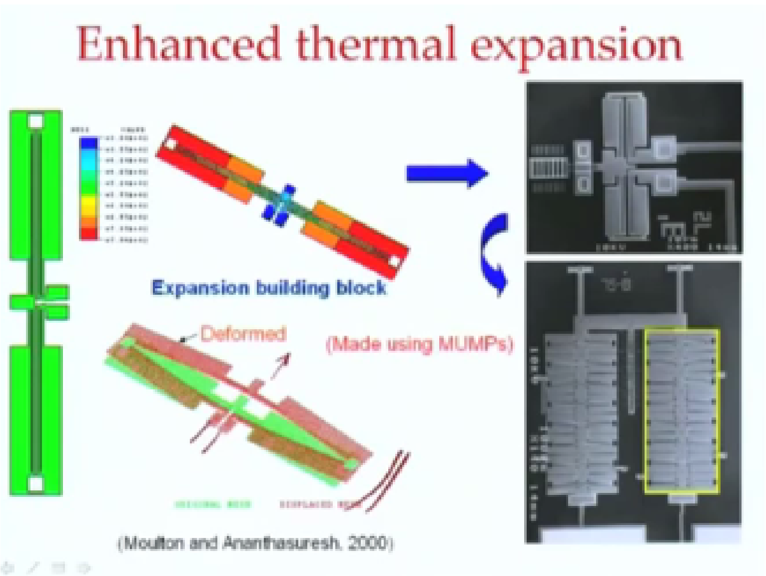

And produce actuation that you want or a combination of force and motion the way you want can be configured based on the geometry. Here an array of such elements is shown that is, if you look at a block such as the one that is pointed here which has an element such as this, which when apply voltage between these 2 points, it is going to move this way and produce a displacement.

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And if you were to block the displacement you will feel the force, so actually it is acting like an actuator. One of them may produce a small force may be other of 100 micro newtons, if you put 10 of them, you will get 10 times that value which can go up to even 1 million newton with a micro actuator and here is a mechanical linkage that was formed with these actuators put in these 3 places.

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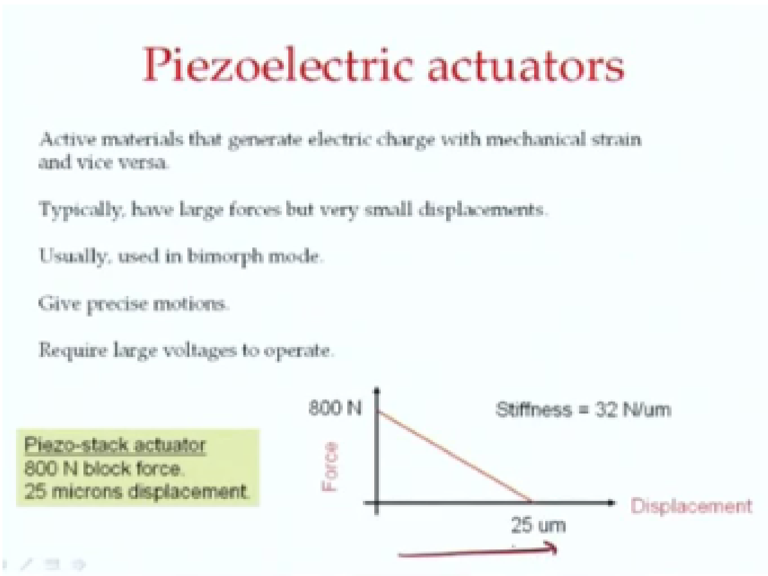

And another view of that where we have a number of these actuators that are going to make this central platform move in the X direction or Y direction or rotate. So, this is an example where these actuators are used to do something different like we do we use a motor at macro scale and do interesting things similar thing can be done at the micro scale using these actuators. Let us look at the piezoelectric actuators which are widely used in many applications.

Especially; where precision motion is required. Piezoelectric materials are smart materials which produce motion whenever electric field is applied across 2 surfaces on those piezo electric materials they produce very large forces of the order of 100s of newtons or even 1000 newtons a few kilo newtons but the problem with them as the example shown here, they produce very small displacement, 25 microns is a typical pairs of stack actuators.

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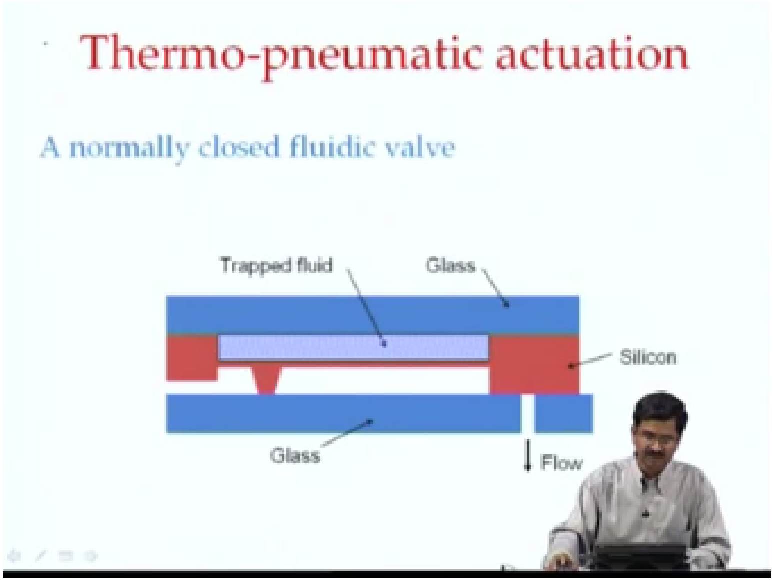

It is not one actuator, many of them are put together to make a stack and that to produces very small displacement but if will so precise that it is used in several precision stages. One can also have pneumatic actuation where you can have a trapped fluid expand either because of heating or because of a chemical reaction.

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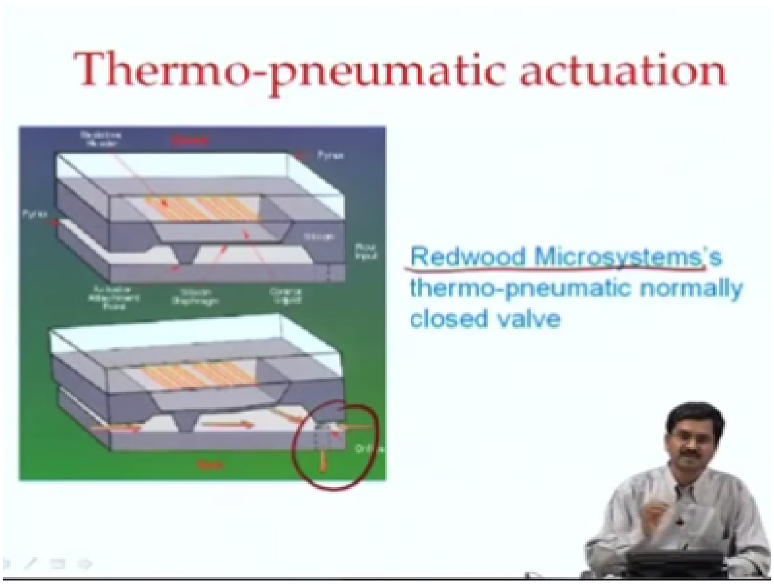

And you can have this expansion used as an actuator to make a fluidic valve there is a commercial device which is shown in this figure where when you heat it that trapped fluid expands that makes this actuator move up and opens a hole or an orifice that is shown here. This is a commercial thermal pneumatic activation that is sold; it has been sold for many years by Redwood Microsystems.

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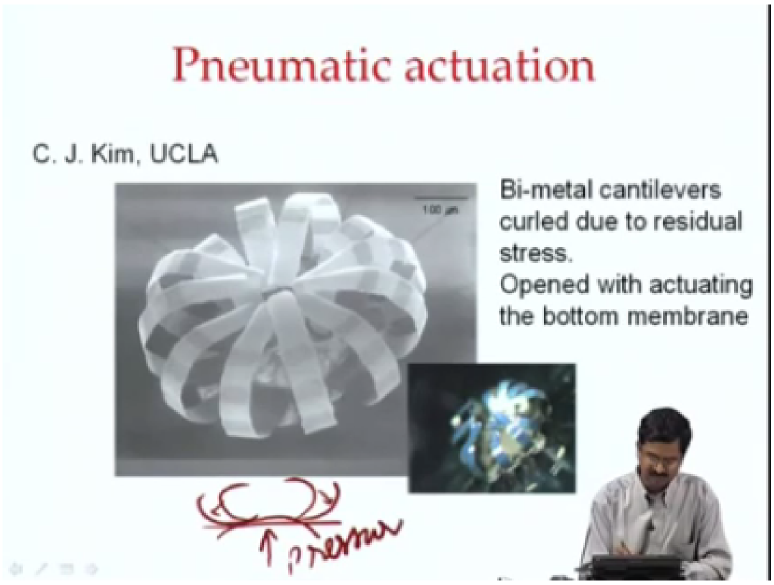

There are a number of commercial actuators such as these they may not be of micron size but they will be small enough that you can use them in micro applications. You can also have pneumatic actuators where a set of beams that are curled up and if you have the membrane over with their sitting; let us say the membrane is flat like this and we have this curved beams the moment you supplies pneumatic actuation from underneath, the membrane would deform like this and it will make these open up, what were here will open up like this.

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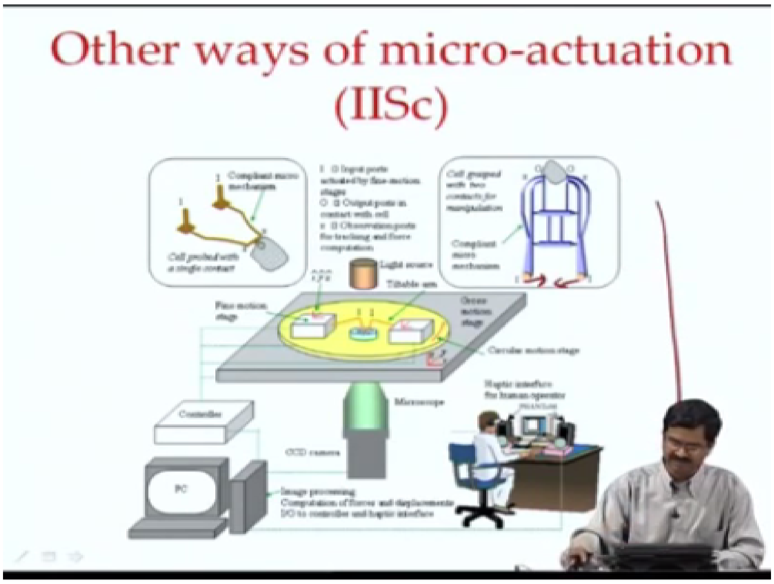

And you can have it like a cage that is operated with the pressure supplied at the bottom, so you can use pneumatic actuation. You can also actually move them physically with micro stages using piezo stages that you see, if you want a gripper where you need to apply force these 2 points to grab something that release it in the presence of a microscope environment which we see a picture to make this clearer.

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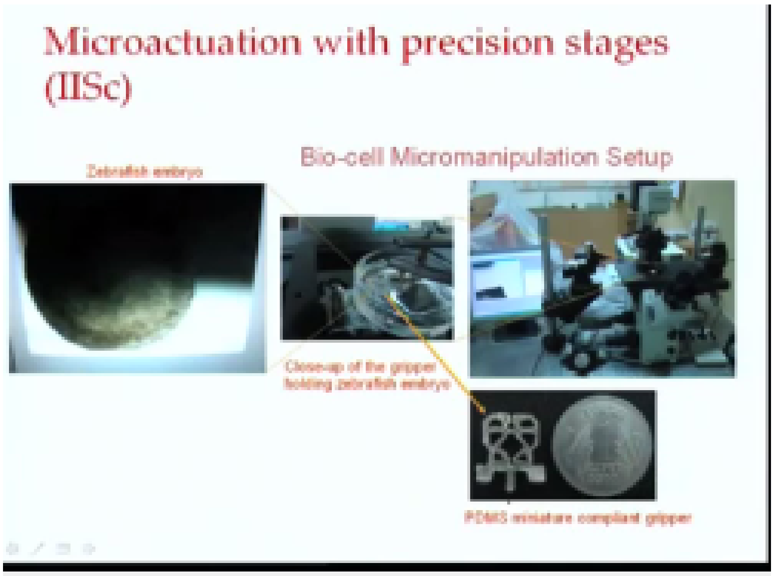

Where, we can have the ends of the gripper or a force application point, we can move it with the help of micro stages that are there which are usually piezo stages or DC motor stages which are big in size but you can use them because they are very precise to move something small and hold even a biological cell with the help of these actuators, which you see here a biological cell being grabbed and moved using these piezo stages which are big in size.

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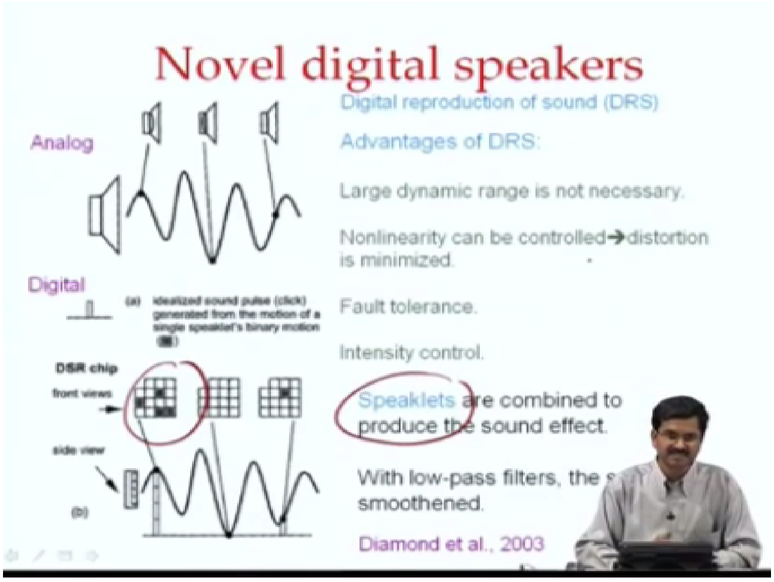

But it can produce small motion, there are actuators as we said speakers; the speakers now instead of using a large membrane to produce sound we can use a number of small membranes as it is shown here which are called speaklets and produce sound in a way that is better than the normal speakers which have a limited linear range, whereas here each speaklet a small membrane will have small linear range.

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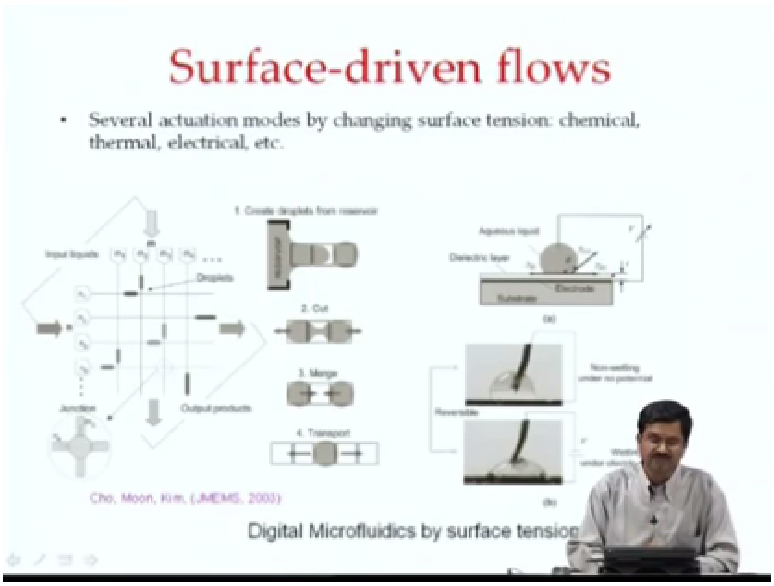

But since we are using an array of them, you can actually get linear range or a large range and that is also a novel design. We do not have time today to discuss this digital speaker designed completely but this is a novel concept in producing sound using an array of these membranes rather than a large membrane. You can also use surface tension effect especially the micro fluidics, if you want to make a fluid move this is a very attractive force which we will discuss at a later stage when we discussed the fluidic devices.

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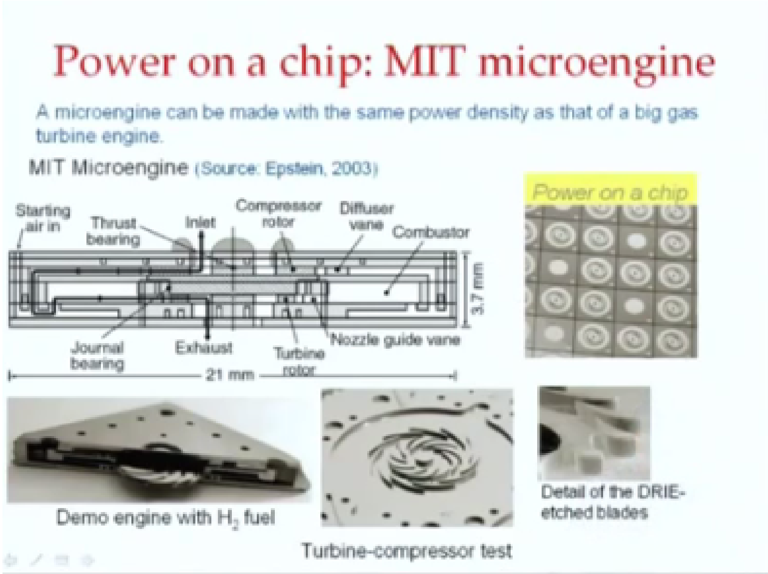

And you can make an entire engine on a chip as is shown here, power on a chip but this again requires a lot of discussion but we just note that we can produce power on a chip.

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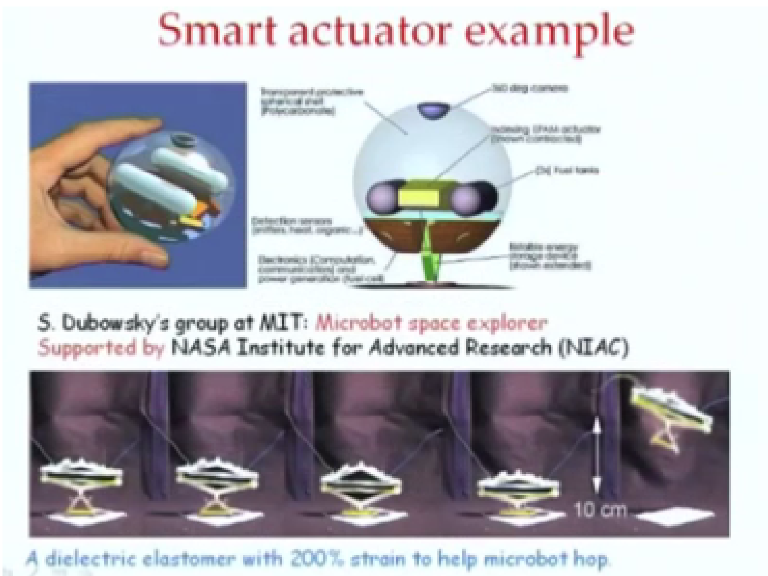

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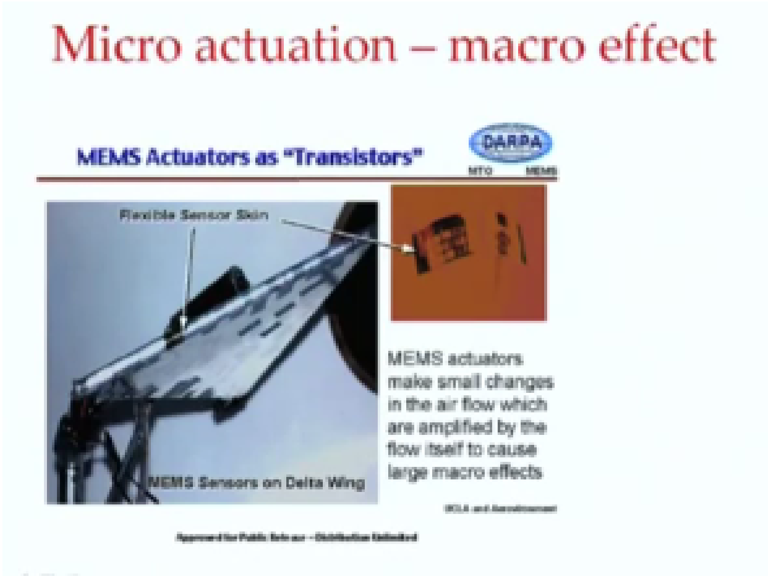

Let us move to one final point that micro actuation need not just move something at the small scale but just that movement at the small scale can also create a large effect such as what is shown in this particular picture here were on the wing of a small aircraft there are the small actuators; micro actuators which when actuated appropriately you can control the turbulence and have very large effects on the aircraft.

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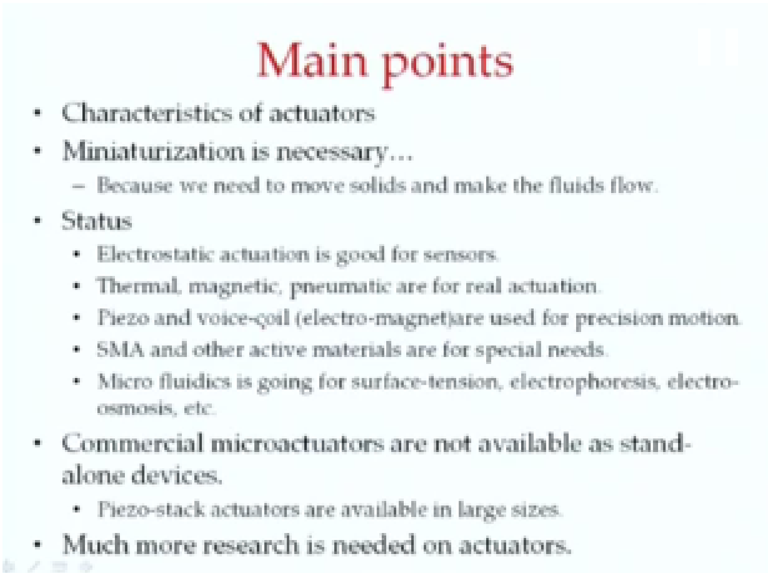

Just to conclude we have discussed a number of characteristics of the actuators and we also discussed why miniaturization necessary because there are lot of sensors that need to be move in order for them to work and number of other applications we need to handle micro things. Today, electrostatic actuation is the most widely used and we have discussed why that is so, in addition to that, we have thermal magnetic pneumatic and other actuations.

And some of these you can commercially buy but most of them are not available yet, piezo and electro magnet in the name of voice coil actuators are available for precision applications they can be bought. SMA and other active materials are used for special needs and microfluidics which we have not discussed today, we will discuss in some other lecture are used in moving fluids in a controlled manner using surface tension effects another phenomenon called electrophoresis, electro osmosis and others.

A lot more research is needed on micro actuators and as we go along in this course we will appreciate why micro actuation is needed and why much more research is needed to make them more and more capable. Thank you.