Compliant Mechanisms: Principles and Design
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Lecture – 65
Materials and prototyping of compliant mechanisms

Hello. Today we are going to talk about Materials and Prototyping of Compliant Mechanisms. Throughout the course we have seen a number of prototypes, a number of devices and we have shown the video clippings of what they do and we actually showed you about a AD compliant mechanisms that we have in our collection, our database. You may wonder how these are made; especially those of you who want to work on compliant mechanisms you should know what materials you can use to make them and what techniques you can use to make prototypes or even manufacture.

So, let us look at both of these aspects now - materials and prototyping.

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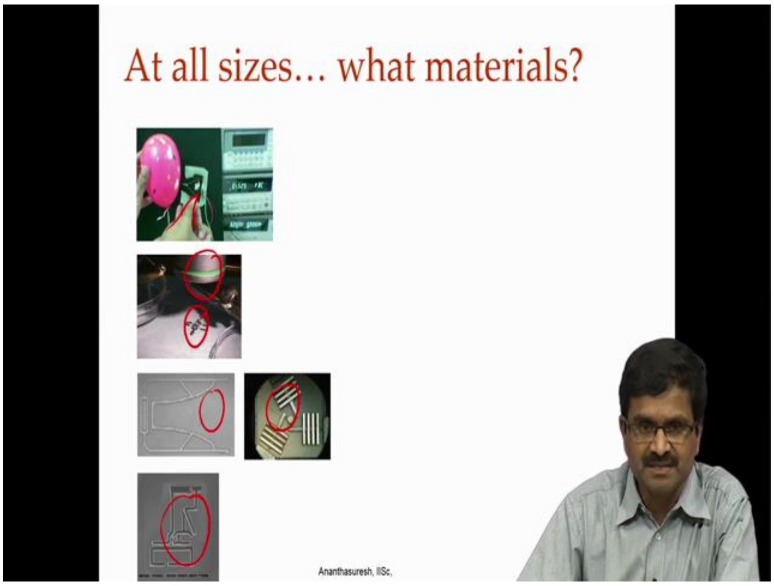

And now we have compliant mechanisms at all sizes, and what materials are used we can see a human hand here. So, you know that it is large and there is a microscope objective here you know that it is small and you can see a SCM and you know these are small. Anyway, but you have something that looks like an SCM but it is actually focused on beam, machined, silicon that is actually at very small scale sub micron or nano meter. So, size does not really matter for compliant mechanism, you can make it any size you just have to choose the appropriate material.

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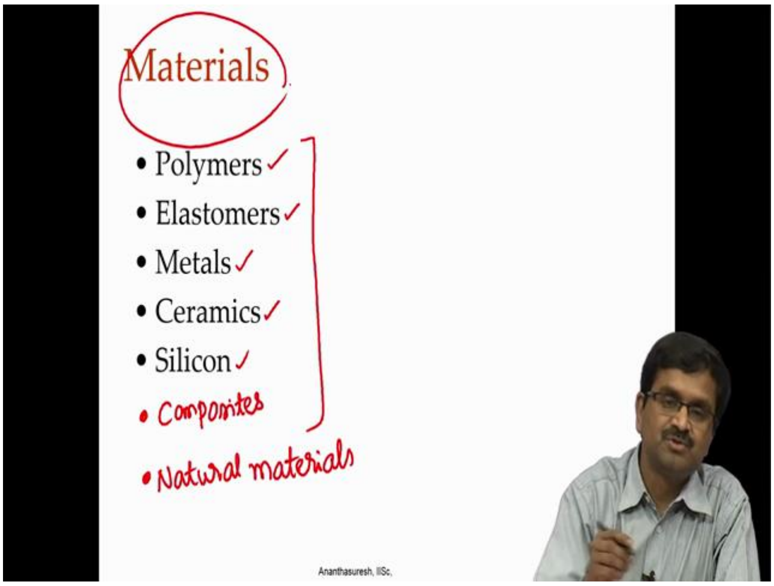

So, what materials are used for compliant mechanisms? Most often we use polymers, the plastics: plastics are of two kinds; polymers and elastomers, elastomers are more like rubbers. In the last lecture we discussed this fluid filled elastomeric enclosures are free, so these are elastomers spinning rubbers which are very flexible materials sometimes people call them soft materials with those you can make interesting compliant mechanisms. And we have done that also as you will see examples, but most of them are polymers.

But we have also used metals as we will see some examples today and we are seen throughout the course. And ceramics too they are not excluded, and then silicon at micro scale because lithography exists for making interesting miniaturized compliant mechanisms for micro electro mechanical systems. In fact, any material can be used and you can use composites also. So, no problem for they are good because you can exploit their anisotropy for making interesting compliant mechanisms.

So, if you look at the different class of materials pretty much everything. I have not written natural materials here, but people have been making compliant mechanisms using natural materials like leather and wood and so forth. The ancient the bow and arrow the bow is actually a natural material and that is a compliant one, because the energy stored when you bend it and that is what you get it and also in the string. So, natural materials can also be used, but today we do not use as much because of lack of consistency in the material, but this is not excluded. Basically you can say that just about any material can be used to make compliant mechanisms.

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And one concern that anybody would have while choosing a material for compliant mechanism is that if I make this material will it not break. So, I have to be always been idea, that especially when I say there is ceramic then you wonder when it is going to break or not especially brittle materials. Now silicon is a brittle material, and one would think that it is going to break, but see that it does not; what I have here is I am holding a silicon wafer here and what we will see is that if I play the movie. So, what we have done in is in the silicon wafer we have cut a spiral a square spiral, it is all in one plane and you can actually see that I can move it, it actually starts vibrating and we can press it this way that way. So, you have actually silicon wafer here which is very brittle if I drop it is going to break into pieces, but we can make it flexible.

So, let me play that video again, so we are able to make that. In fact, it is like a silicon slink I can take it and remove it up and down which I have in my hand not silicon.

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So, what I have here is an acrylic piece which I had shown earlier and it is just that on the side I have just attached this rod so that I can I can pull it. So, this actually acrylic piece with a laser we have cut here into a circular spiral, so it is all acrylic piece there and is just the rod is just attached right you can see the other side. And now I can push it in and out and I can make its very very flexible. It will not break because its design is such that the strains are not high as stresses are not high and the displacement is very high. So, I would always argue I have not made one so far is even I take a slab of granite if I cut a spiral I can make that a spring something like this.

So, it is a question of design if you want to achieve compliance or flexibility nothing to do with material, of course you have to design according to material property.

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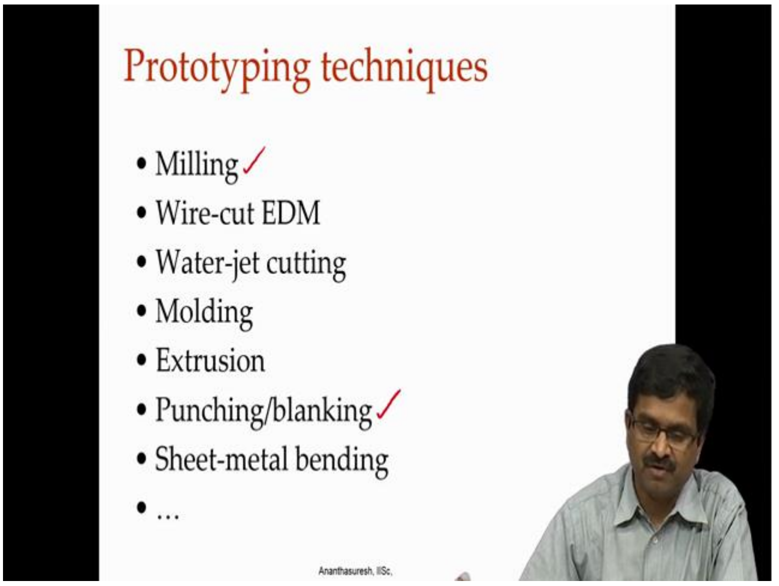

So, what prototyping techniques can be used to make compliant mechanisms? A number of them are listed here. So, we can do milling take a sheet and cut. So, most of the mechanisms that we have made are used by milling or made by using milling. So, we can take mill bits of various diameters depending on the minimum feature size that you have and cut it out. We have also used wire cut electro discharge machining that is for material that is conductive. So, that can be done for the metals I will show you some examples. One can use water jet cutting and molding like injection molding. We can also do extrusion, especially we have planar compliant mechanism make an extrusion the whole mechanism will come out and then we can just slice to make that will be a batch production type of technique.

So, all of these are you know batch production amenable. And we can do punching and blanking so that will be interesting thing we will see that. And sheet metal bending you can make something in a plane and then bend it out of plane to make interesting three dimensional compliant mechanisms. Just about any technique I just put dot dot dot saying that anything that is there you can adopt it for making compliant mechanisms, because we just need to take a material that is available and cut out some shapes into it in order to get the design that we have for compliant behaviour.

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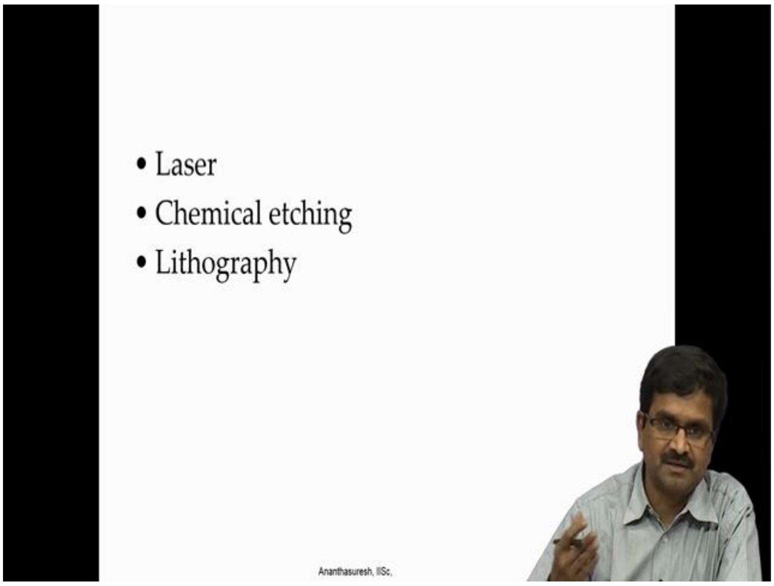

We can use laser, chemical etching, and lithography and chemical etching combined for miniaturization. So, these are also possible. So, number of techniques at large scale and small scale small sizes one can use to make compliant mechanisms.

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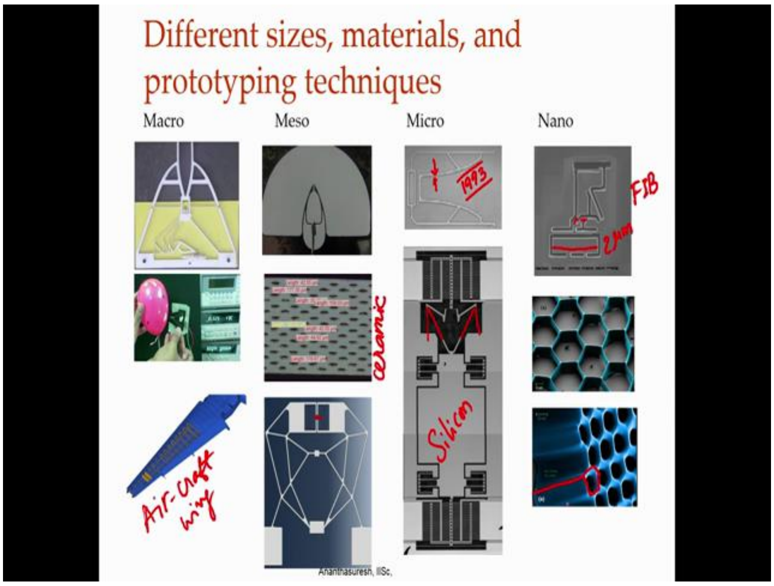

So let us look at some example; macro size we have this mechanism polypropylene among the plastics we use polypropylene a lot because it has a right low character characteristics of being having low Young's modulus and high strength. So, polypropylene is also is available widely and that is used here. This entire mechanism was done by milling out of a large sheet. There are very thin beams, but milling can be done. And there is a metal one and this is a 3D printed, one these are all large this is actually air-craft wing. So, very large ones also be done using compliant mechanisms, we have seen those examples already.

Now, we come to slightly small then we have this metal one. So, it actually been fold and you can see that moving we will see a larger one and here is a ceramic. So, this particular one is to increase the fracture toughness of armor. So, there is a little not really a lot of compliance, but enough to increase the fracture toughness and this is a 3D printed one that will saw the meso-scale. Already we saw the video of this where it grab something and stretches it.

Then we have micro. So, this is actually I would say that the one that was made in 1994 or actually less than 1993 I will make it. So, it was then back then it was my first micro compliant mechanism most likely the first in the world as well. And more recently an accelerometer where things are you actually do not see these beams here, there are tiny beams which are only if I my microns void so at that time it was more like 15 microns void band, even then we could have made small but it is a first one to try and the micro level that is something can be made out of silicon. So, this is silicon.

Here is one that is actually nano this was done using focused ion beam milling. It like milling, but you do with ions. And this was made like two microns. So, you can imagine other features, so this is small flexures here which are very very small. You can do the focused ion beam milling to do that is a more recent work where we have high expects ratio structures that we are using in some cell culture scaffolds. So, we can have very high hexagonal structures and various other things. This was done using some kind of super resolution lithography.

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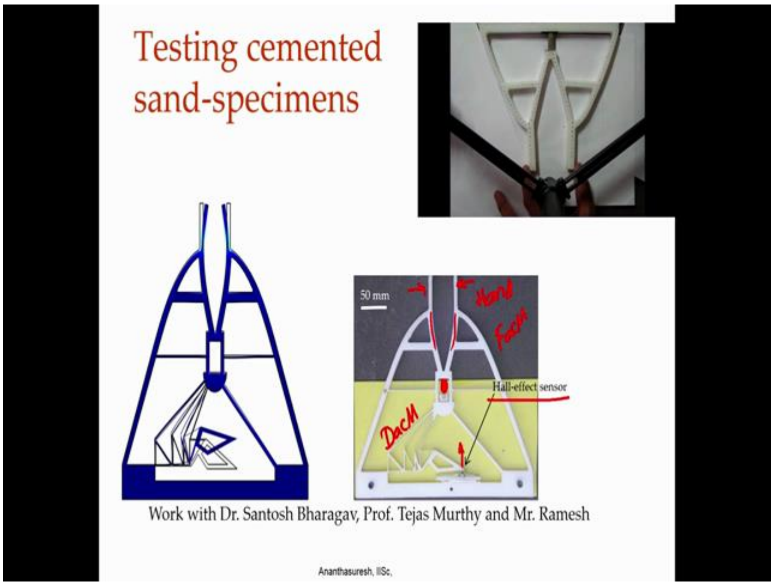

So, let us look at a few examples to look at macro, meso, micro, and nano, and how materials and prototyping techniques come together to make compliant mechanisms that are interesting. This one as I already discussed in another lecture so this was to have a cemented sand specimen here with hand force anybody even a kid can press this and crush this cemented sand specimen. So, because this is n FACM; what you call composite compliant mechanism. And then here we have a DACM; displacement amplification compliant mechanism that based on the force it will move this way very large amount you can put a Hall Effect sensor if a displacement and measure this force.

So, here we used basically milled thing here, eventually if somebody wants a product that of it can be injection molded. So, here is the video of that. So, he cemented sand specimen is over there we are applying force by hand; you can just the couple of fingers, you cannot even you know. You can hold it of course you cannot really crush with your fingers, whereas a FACM enables to do that.

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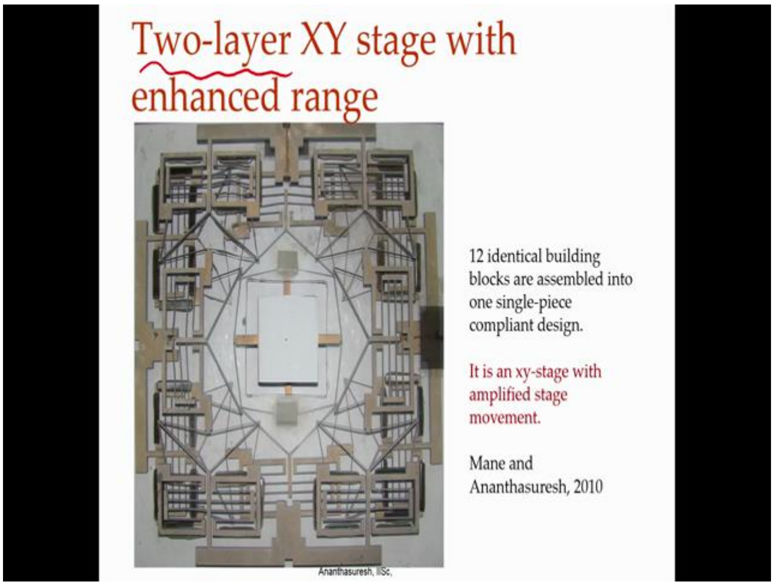

Now, here is one that was made with wire EDM, looks complicated. It was aluminum or spring steel very complicated device lots and lots of beams and its was made in two layers - it is an xy-stage with enhanced range. So, metals also can be used very happily.

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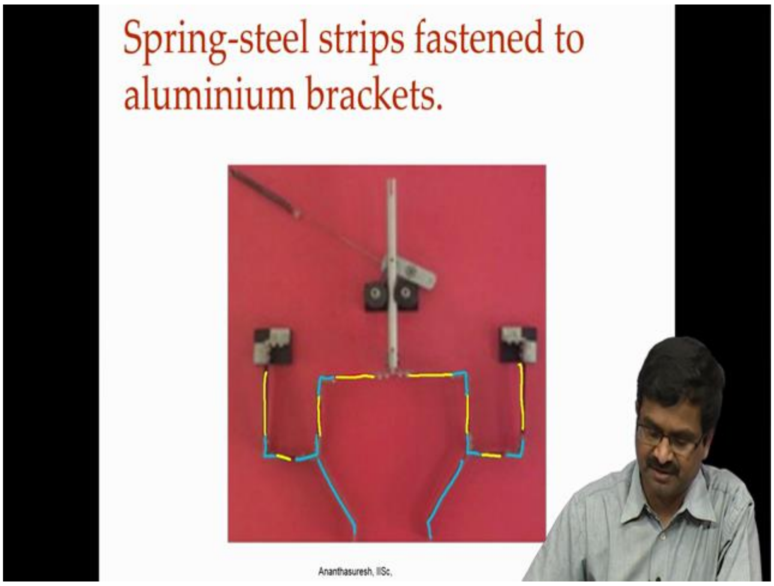

This one we have discussed in the context of static balancing where we have this; I have to use a different colour, where we have this beams here which are spring steel strips and then there are aluminum brackets. So, aluminum bracket let me put in different colour, sothese are aluminum brackets. So here, here also I forgotten couple of more spring steel strips this one, this one. So, you can make with metal also its not single piece in the sense that we can just take one and bend it which you could, but we happen to see that it is a better way of doing here Professor Prasanna Gandhi; IIT, Bombay is doing a lot of work on making compliant mechanisms using this type of technique.

Now, let us look at couple of examples of meso-scale, something that centimeter to about 100 microns, not really micro but bigger than that.

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So, this is the metal one. So, this will be I think 2 centimeters. So, here this were like more like 1 centimeter and this probably was maybe count of a millimeter or something like that. You can see this metal and highly elastic we are put a little, but you can do with your hand also make little a gripper. So, it is a spring steel gripper.

So, what you have here is a spring steel gripper that we looked at how it works, and now let us see how we can make it. This was made using wire EDM. So, very narrow reentrant kind of structure they are all cut using wire cut electro discharge machining, but this will not be amenable for batch production, how do you do this using batch production; meaning something I can assemble and all of them should just come out you know 100 per second or something like that.

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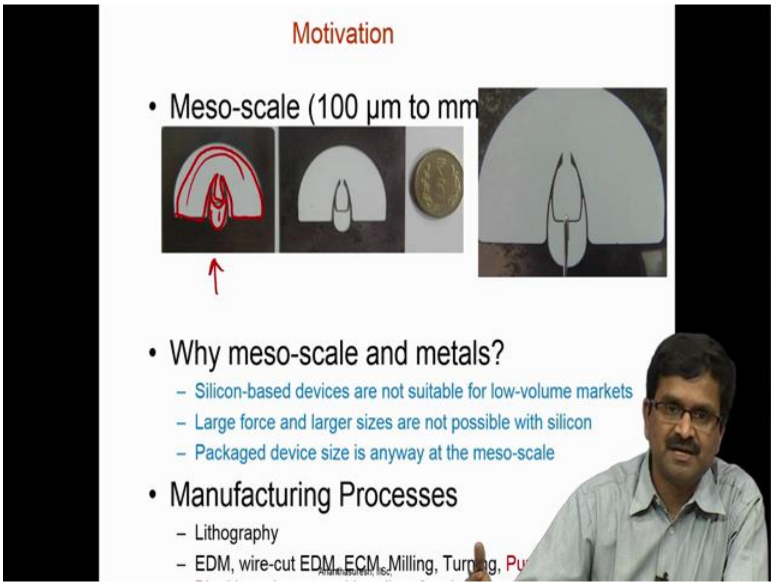

So, one can explore adapting the existing manufacturing processes at the large scale to meso-scale. So, the idea is that can be made this gripper by punching or blanking. So, there is one hole here and there is hole this one hole by that I mean a hole like this I can punch that and I can punch the one in between and I will be able to make this using like a batch production processes, because the laser whatever you do it is not going to be economical, whereas punching is economical. In fact, that is what we did. So, we can go from 100 microns to millimeter or centimeter scale devices very easily with this punching.

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For that you need to have; this is wire EDM you know this will be very expensive very slow. But then you see a lot of craft punches that are there now that we can buy in the market: craft punches. So, here is one that has the maple leaf for die. You can punch out of metal we have done this in paper that is 150 micron thick paper and then there is aluminum foil, you can this various shapes.

And what the question we asked is that, how narrow a beam can be punched, so that if I want to leave a beam there I have to punch this hole and that hole. Or for making this compliant mechanism I have to make this big hole here of a complicated shape another hole over there, then I can make this two holes.

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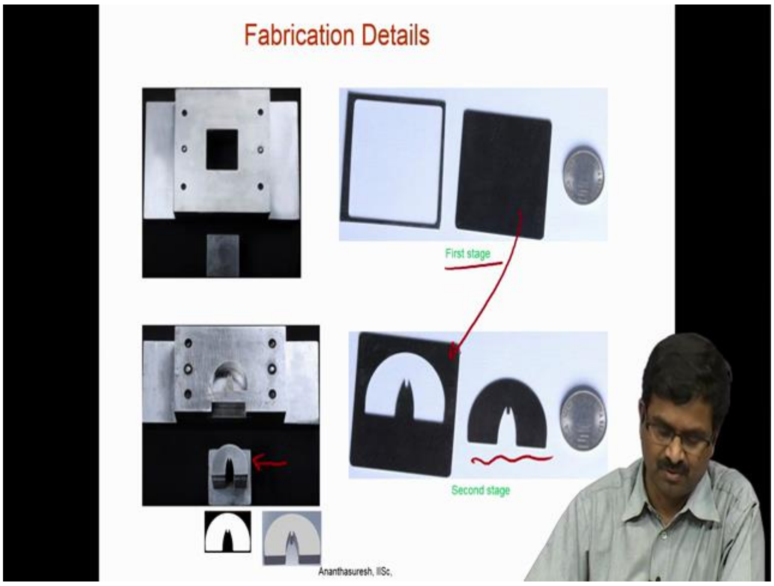

But that will be quite difficult, so but by splitting into several stages you can actually get this done which is what we ended up doing by making the gripper that I showed you. First we take a sheet and blank it out so we get this first stage. Now we will make a square thing and the die for that is shown there and there is a matching punch for it. And then we make another die which is like that which is going to punch this hole here, so we get that, we get this thing out of this here.

So when you have that, we make this hole; that is one punching operation. And then take this to the next level. And take this device now; what you punch out that will be there that we throw we are use it that is another idea. So, we have taken this thing here and punched one hole.

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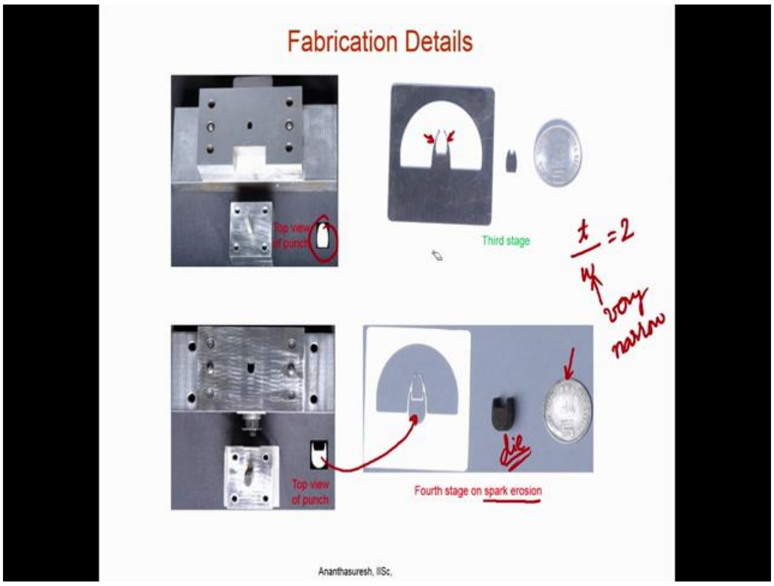

Then you go to the third level where you have another little punch to make this one. Because previously, so we have done upto this now we have to make something more here another hole and that is done there that is the third stage. Forth stage is this particular hole. So, this particular one so you can actually cut this out. So, with this one you punch it out. So, this is the die for it. So you can make that, this is the 5 rupee coin and we can make this in four stages we can do it, but forth stage we actually ended up using spark erosion because already there are this very thin beams are there and when you punch you might actually bend them and break whatever. So, we actually use this die and use spark erosion rather than wire EDM. That is going to be slow, but our idea was to explore this and take it further.

In punching we also did like of modeling to see; what is the narrowest beam that you can punch and what is the aspect ratio of it; that is what the thickness there is a thickness for this. So, if take thickness divided by a narrowest feature that is w making it equal to 1, one can just use chemical etching that is not a problem but we wanted to be a as large as possible. We are able to achieve 2; the idea is with punching can you punch due to thick materials and have a very narrow beam left; so very narrow beam.

So, if we can adopt both punching as well as sheet metal bending we can actually make very interesting compliant is out of metal which will be meso-scale and that is the going to be competitive against lithography based MEMS sensors accelerometer and gyroscopes and so forth. Those sensors are small, but when you put this electronics and package and everything this going to be meso-scale they are not going to be micro scale; they will be millimeter, centimeter scale. But the sensor element does not need to be small if there is a batch production technique such as punching.

The advantage of a batch production such as punching is that; even if the size of the lock that you want to make is only 50 or 100 it is economically justifiable but lithography will not be justifiable. And the whole die set that we made for this application was not exceeding 30000. So, it is possible to adopt existing processes for making compliant mechanisms.

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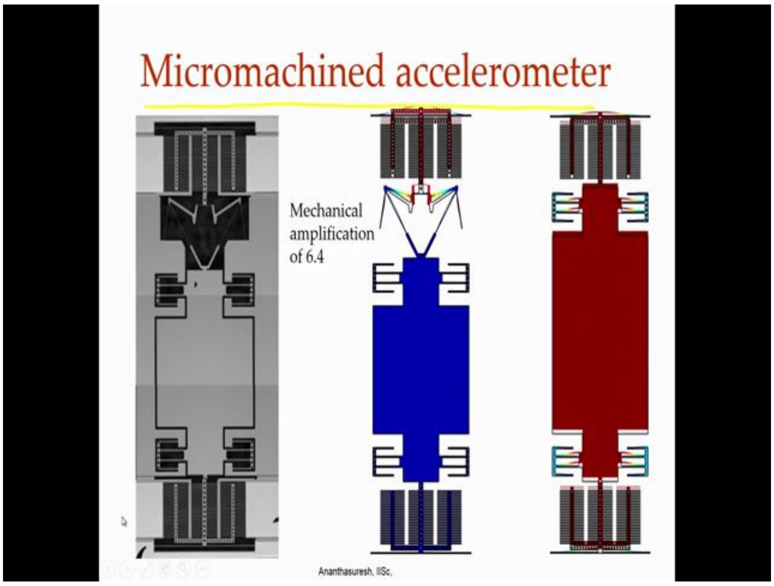

And this we moving on to micro we have lithography. We will be looking at this micro machine accelerometer in a case study little later to at the end of the course; that is next week we will look at this then we will discuss how we can make at the micro scale.

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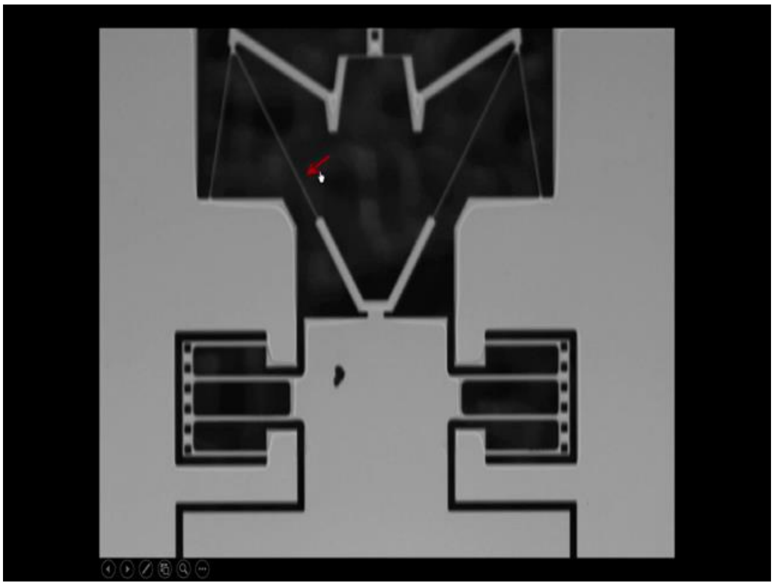

And there is a close up view we will see the movie. So, you can see these things they are so thin they are more like you know wires or strings, but it is silicon and it does not break; we have used it packaged it and all that it works in most of the beams in micro electro mechanical systems devices are really thin, and they work and you do not have to worry about the breaking.

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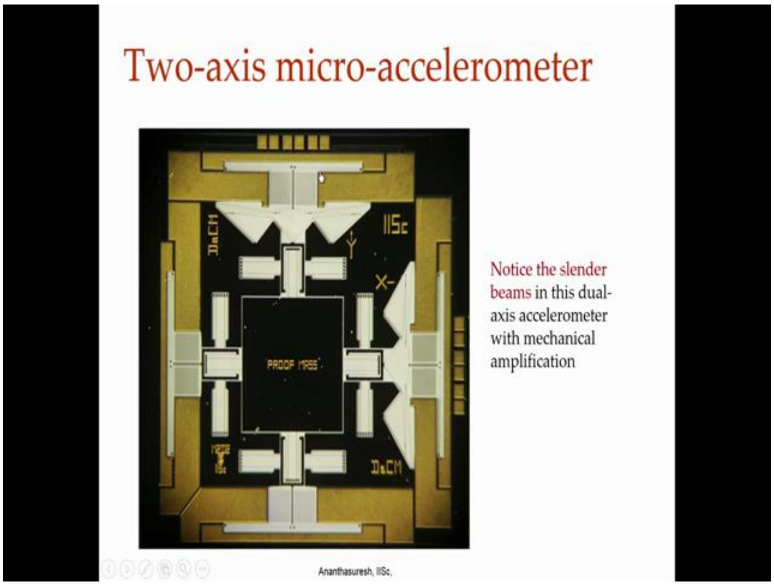

So, here is a two axis accelerometer details later in another lecture.

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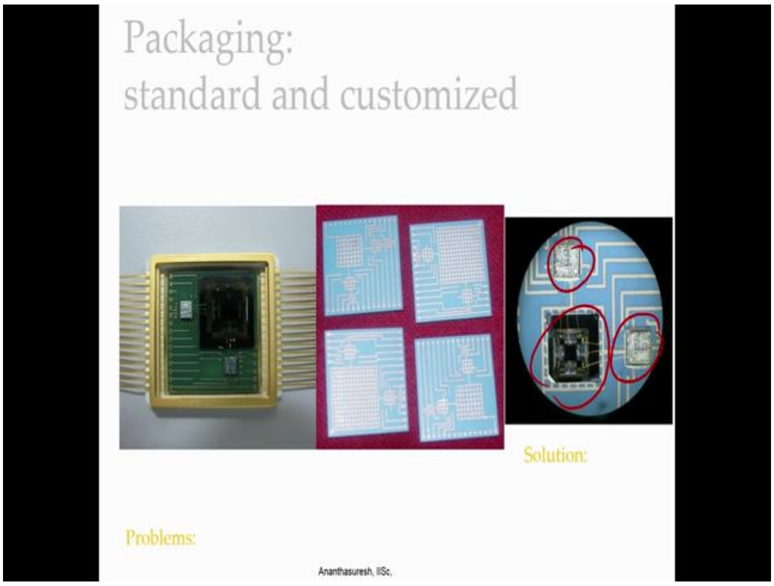

So, it is all packaged into where we have the asics for electronics and mechanical chip is over here.

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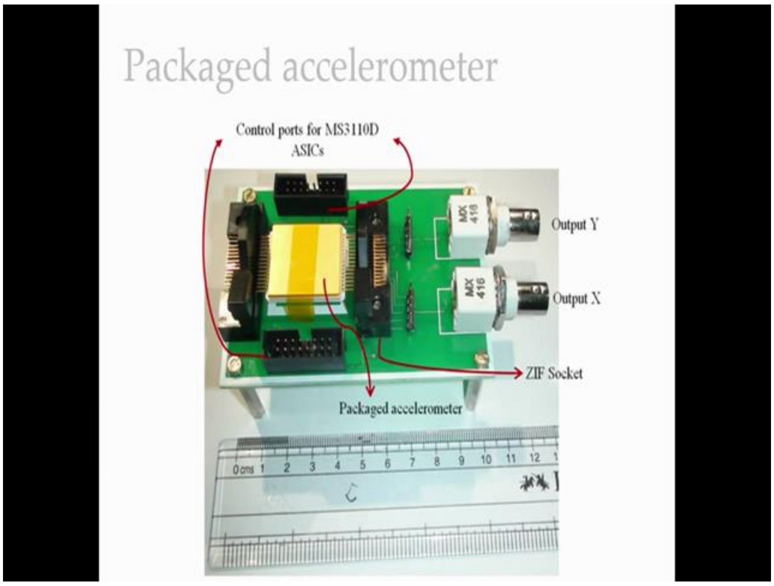

And on a ceramics substrate and it is packaged and it works as long as you want.

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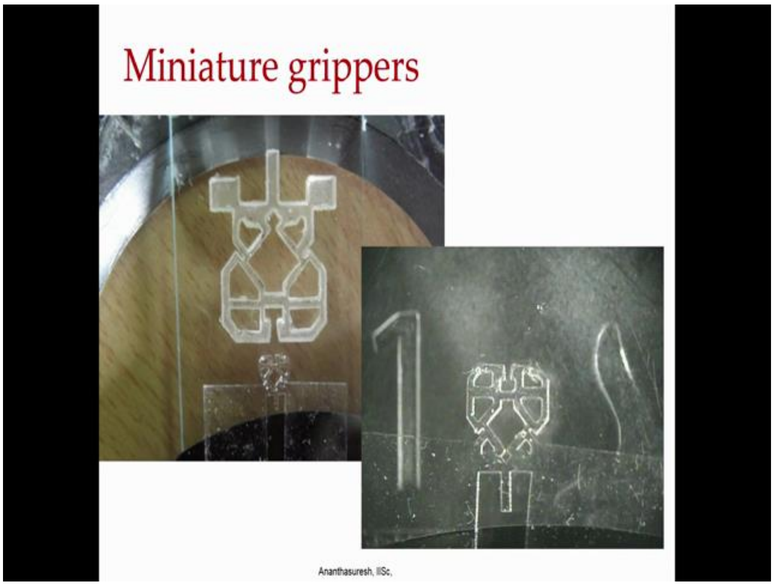

We also have this miniature gripper. There is another lecture on that where we use this SU-8 and PDMS material. This is PDMS where we can make grippers with which you can manipulate biological cells as we seen in a future lecture.

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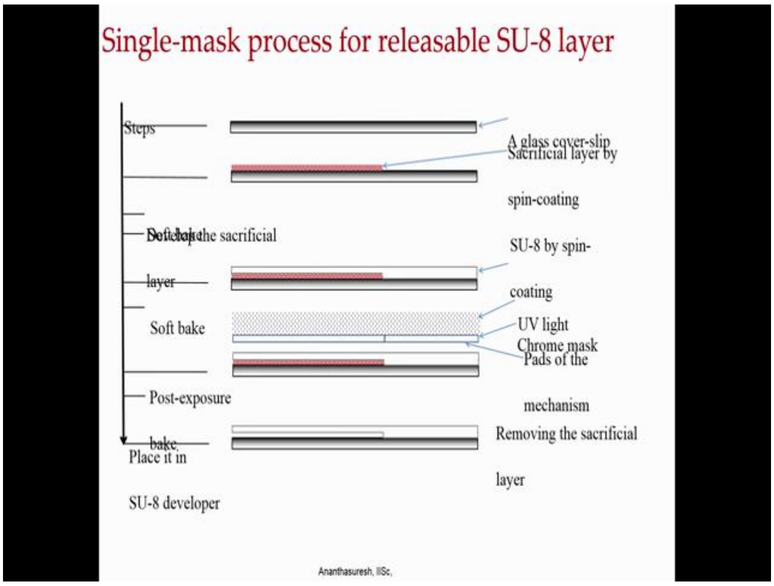

And here we have the process for making this. So, just lithography you deposit the material and pattern and create the shade that you want as a multi layered structure.

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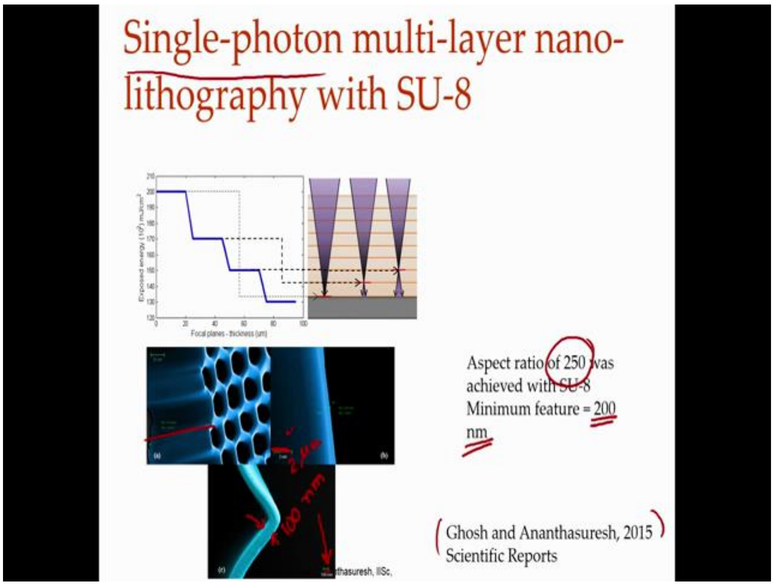

We want to nano, we have this focused hand beam milling machine which I had shown. But this one is a some of the super resolution lithography there we have single photon multi layer nano lithography using SU-8 material where you can get very high aspect ratios details of which you can read in this paper.

So, minimum feature size was 200 nano meters and the length of this was very high, this line that you see here this line that is 2 microns. So, clearly the height of this is much more than that, whereas here if you see this is 100 nano meter this little line that you see there at the bottom. So, I do not know whether you see a little line is 100 nano meters. So, this one is more like 100 nano meters, this is 2 microns. So, you have such a large 2000 nanometers is 100, so you have the aspect ratio. In fact, you can go the aspect ratio of as much as 250 also here.

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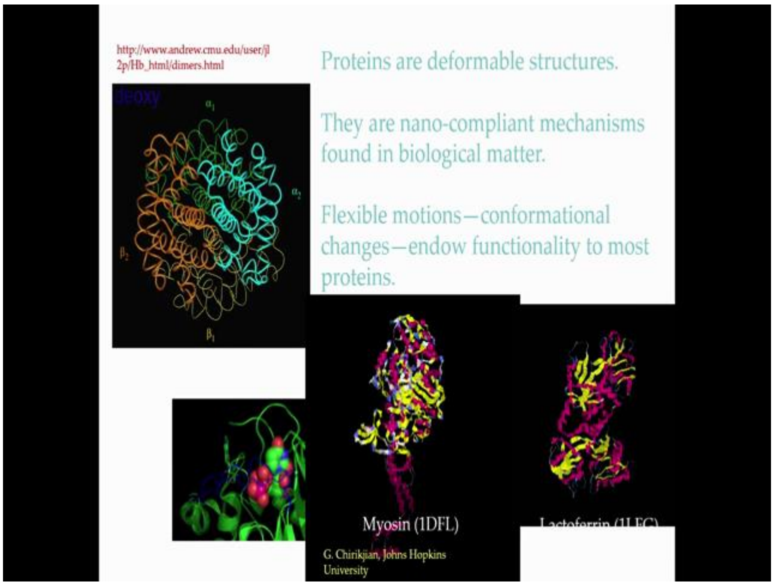

If we go down to biology at nano scale we have actually proteins. These are also in a way compliant mechanisms and in fact some of the design techniques that we have for compliant mechanisms can be applied to these also. These are simulations taken from Professor G. Chirikjians lab at Johns Hopkins University. However, numbers of them like this. And they basically move they are compliant there, they are not like rigid bodies segments put together with joints. The proteins are really wonderful nano scale compliant mechanisms. And the way nature makes them is a very efficient prototype technique which we cannot that nature does.

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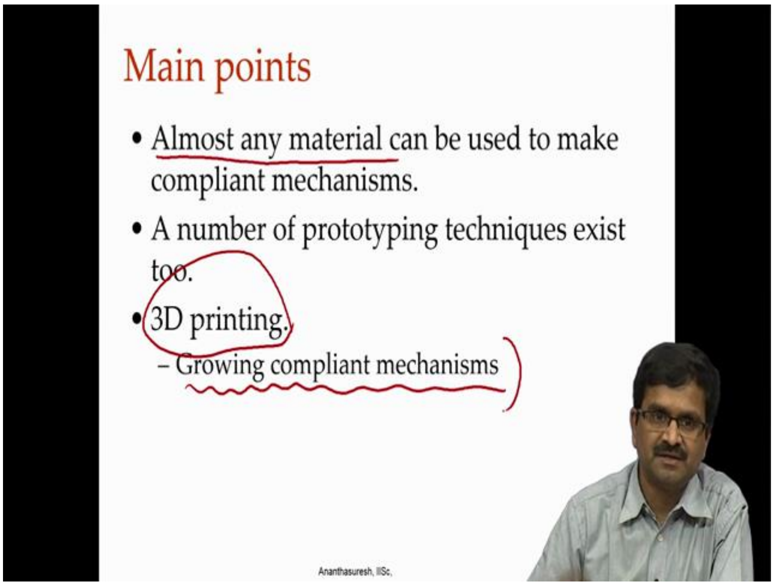

To summarize almost any material can be used to make compliant mechanisms and that you know. Almost any I underline, any material could be used it is a question of right design for it. A number of prototyping techniques exist. Whatever is there you can use it to make. And 3D printing that makes your life easy. And this is making the interest in compliant mechanisms grow, because just about anybody can make that now without much effort otherwise when you make it milling you have to have the right fixtures and so forth, but with 3D print we can do.

But then 3D print technology has a lot to grow, because right now we do not have the properties being constant for a period of time, so you can make an after while till it is actually change their properties. But 3D printing technology will improve at that time one can design and make compliant mechanisms rather easily.

Thank you.