Compliant Mechanisms: Principles and Design
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Lecture – 64
A few special concepts of compliant mechanisms

Hello, we are going to discuss a few concepts of compliant mechanisms that we have not touched upon so far in the course apart from mentioning in passing those. So, we look at those concepts little bit in little bit detail today.

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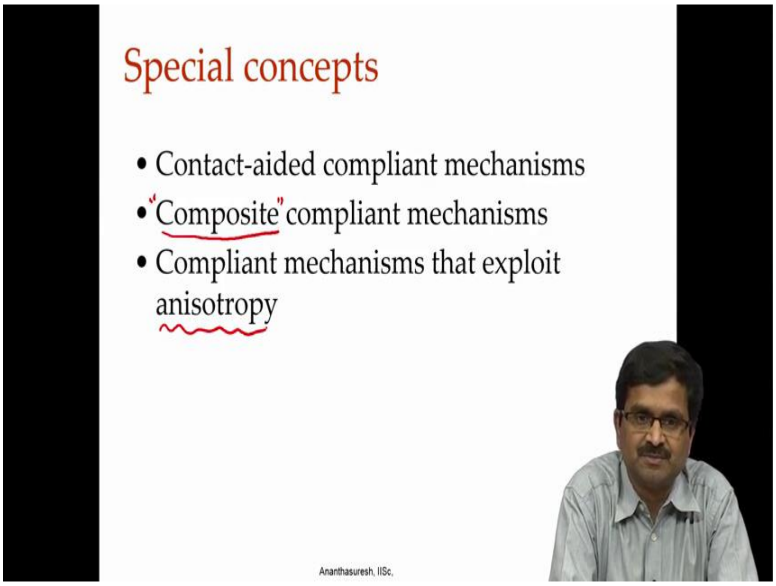

So, let us look at what those concepts are; the three, one is intermittent contact aided compliant mechanisms. We had mentioned this briefly, but we look at what it means for compliant mechanisms design and what we can achieve when we allow intermittent contact and the second one is what we call I should actually put coat, uncoat compliant composite, compliant mechanisms by composite here, we do not mean that compliant mechanisms made of composite material which one can very well make, but here what we mean is combining two compliant mechanisms two or more compliant mechanisms to achieve some unique functionality. And the third one is using anisotropy properties of material to explore new avenues in compliant mechanisms.

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These are the three things that we will discuss today; let us begin with contact aided compliant mechanisms or for short CCM - contact aided compliant mechanisms. So, this C kind of captures everything contact aided that is in these compliant mechanisms, there will be contact as an aid to achieve something unusual and useful.

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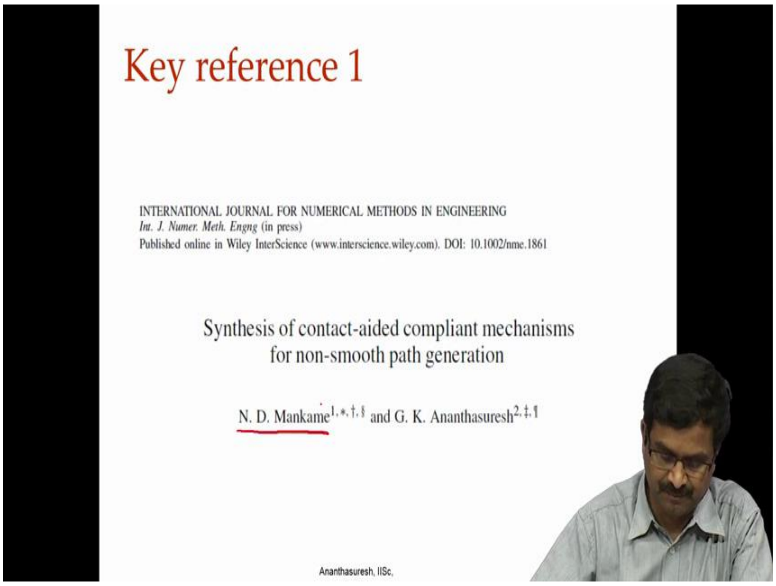

So, the reference here is one of the reference is this paper from International Journal for Numerical Methods in Engineering and author is Nilesh Mankame in fact this work was done by Nilesh as part of its PhD thesis at universal (Refer Time: 02:32) in 2004.

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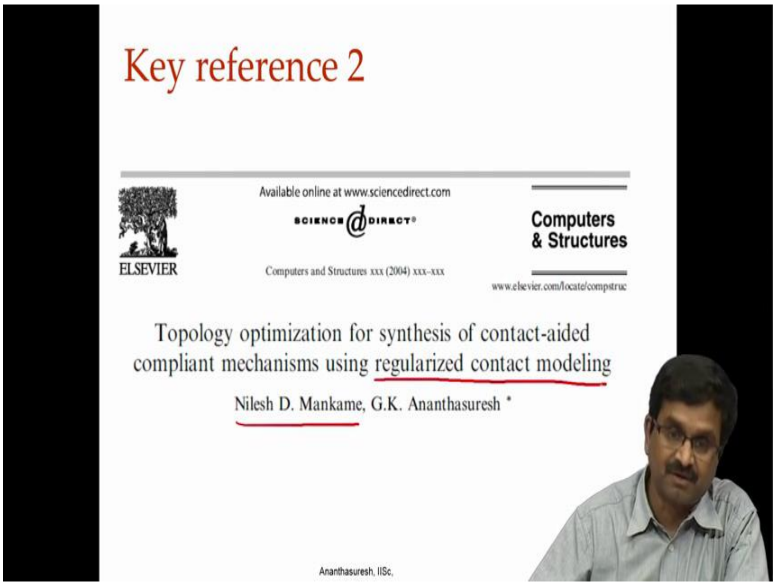

Here is another paper by the same student, now working for General Motors in the US. So, this in computers and structures, so these also another thing where some regularized contact modeling was used to synthesis contact aided compliant mechanisms.

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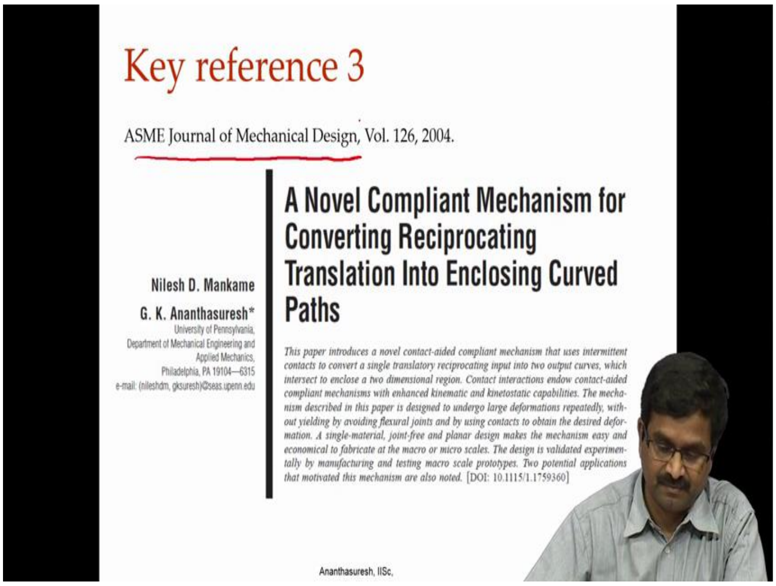

The third one is an interesting mechanism which we had seen a video of already. Now we will discuss little bit more about it, this is in ASME journal of mechanical design, where we can use a compliant mechanisms to achieve complicated parts that have non smooth points in them.

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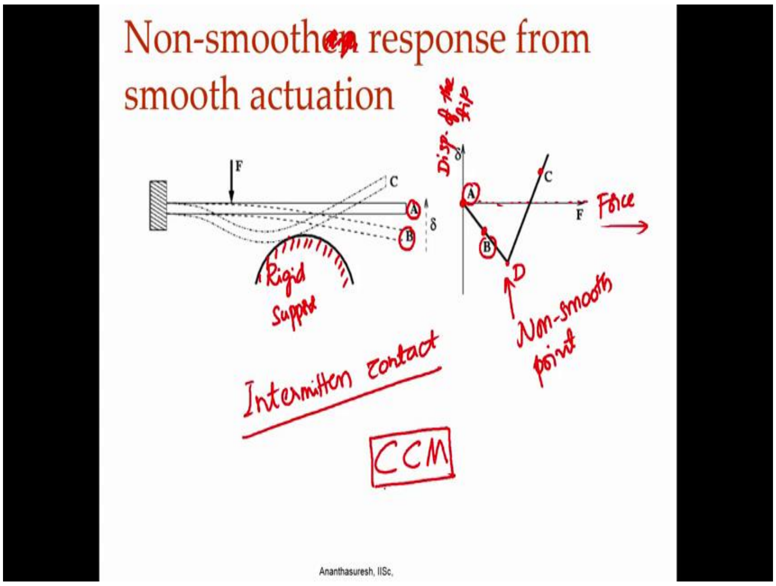

So, let us first look at this non smooth response from compliant mechanisms, when you have only smooth actuation. So, this is one of the advantages of having contact, what you see here A the point A here and the beam A is undeformed, now there is a rigid support here; this is like a surface, so which is rigid and when you apply force the beam will bend come to B. So, B is somewhere we going to (Refer Time: 04:14) there. So, A is undeformed what we are showing here is that displacement of the tip and here we have force, so in force equal to 0 what at A and when you apply some force somewhere here (Refer Time: 04:36).

Now, when you continue to apply force that increase the magnitude of the force at some point that beam will touch rigid surface something like C let say C is somewhere there. There will be a point here which we have not shown there, let us call that D or something where the beam would just contact, so B configuration B; it is the force increase a little bit more, it will come and touch it and after it touches when you apply force more and more force; that is keep increasing your force here. Then this point it is coming down so far will start moving up and it will do so rather abruptly; that is this path here the displacement of this force will have a non smooth point, this is a non smooth point and that is what we want; we want non smooth response from smooth actuation.

As for as F is concerned if increases gradually smoothly, there is no problem where by the displacement suddenly will change its direction and it does so all of a sudden, it is not discontinuous, but it is non smooth. So, when you use intermittent contact, so contact that happens over there is intermittent meaning that it just happens remove the force it is going to go back there is no more contact, you have intermittent contact. And that is what we have the compliant mechanism exploiting here so that we can get non smooth output or non smooth response from smooth actuation.

So, that is the concept of this contact aided compliant mechanisms. By the way CCM is also sometimes in acronym use for computational contact mechanics either way this title is appropriate here because we have to model contact here.

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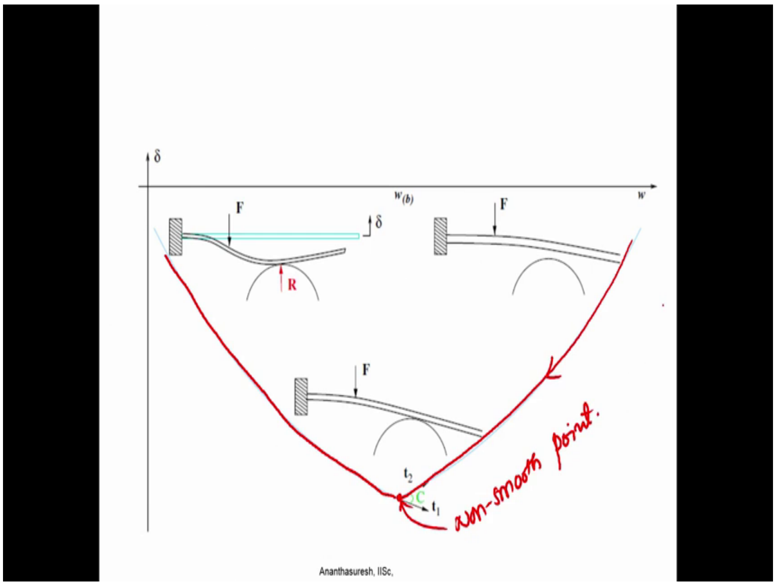

So, let us look at what I just said in the form of the figure, so when you are little bit deformed versus when you are touching and when you are not touching; we see what happens. So, here is the contact thing here, so here this is the force or W is a configuration. So, it starts here this case it comes like this and then goes up after wards, so here we have the non smooth point.

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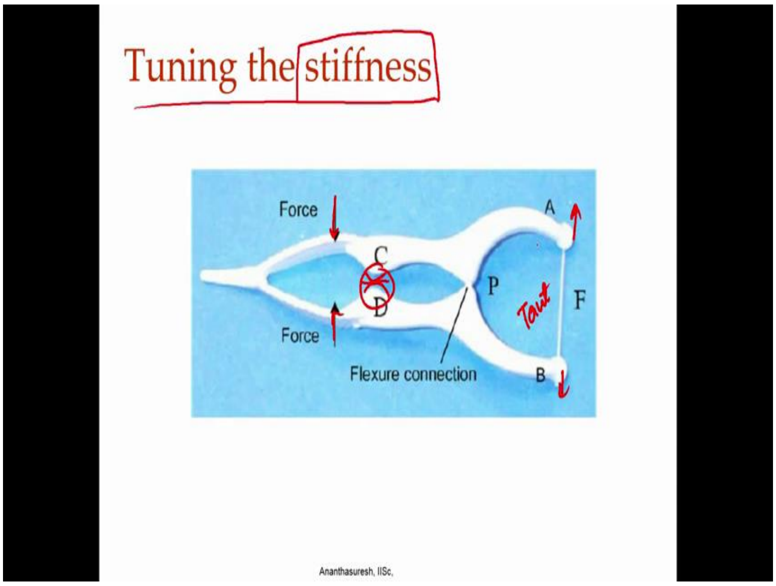

What else can you do in you have contact, the other thing is tuning the stiffness by that what we mean is that during the motion when you are using a device; as you are applying more on more force the stiffness of the structure changed as to be stiffness of the compliant mechanism changes, that is natural where the contact is change the boundary condition that is why I have the non smooth thing there.

You are solving on problem with some boundary conditions, the moment contact happens there is a new boundary condition coming in that changes the entire response of the compliant mechanism in particular here, we see how this stiffness can be changed and here is a commercial device that I happen to half that is basically a dental floss is a little device.

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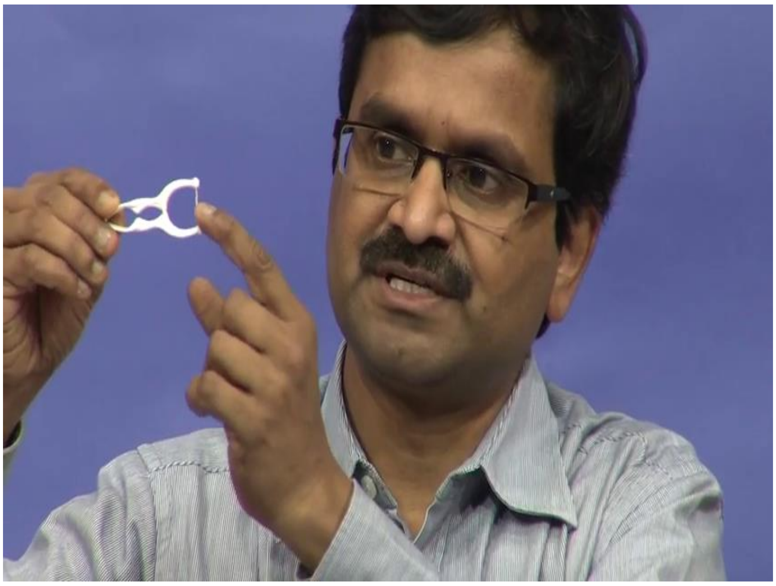

So, it has the floss here which is flexible, so this is just a dental floss which can see it is flexible that, but the moment I apply force here, there is a contact here. So, there is a contact when it touches even if I apply more force, it does not deform this further that is a contact is being used here to change the stiffness right. Now it is stiff and I can have flux it in more, now it is very stiff compared to when it was where I could deflect a lot, the movement I press; I cannot deflect as much.

So, this is a contact aided compliant mechanisms where the displacement is limited to certain value. So, we can tune this stiffness as needed, so here as I showed when we apply force over here, this is where the rigid gap we did not see that that gap closes initially when I press, this point will move like move this way, this will become taut after by the time these two would have touched with each other; once that touch there is a stiffness increase and when you even you apply more force, it does not apply more force this way and break it. So, that is the advantage of having intermittent contact.

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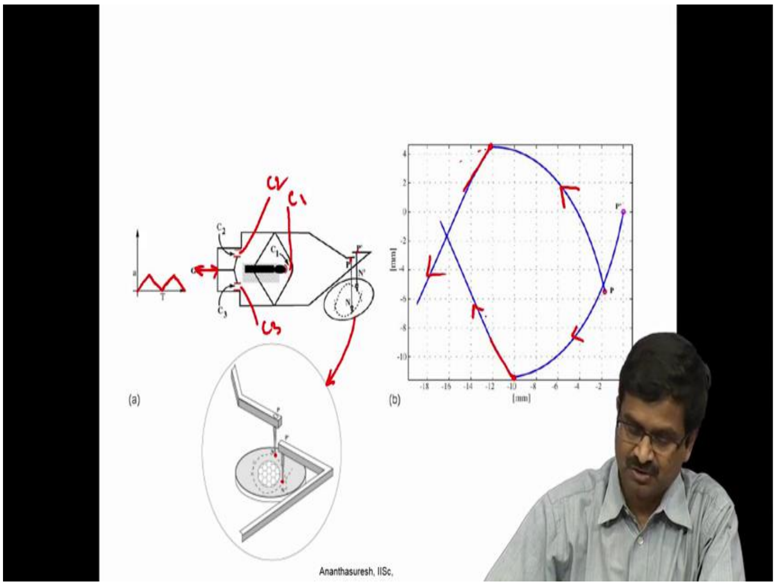

It is another one whose video we had seen earlier this is also a CCM, this is again has a very complicated path generated here again with non smooth points. So, it starts here and it goes there and goes their while this point goes here and goes here; the two points are shown which are over here. So, this part is amplified over there; all we do is smooth input over here back and forth like this; like a sort to this shown here, we just make it back go back and forth, when we do that there is contact here and there is also a contact here.

So, that is written C 1 contact here C 2 and C 3 and because of that these points will generate this paths that have non smooth points in fact, direction suddenly changes instead of just going gradually like this suddenly changes like that and changes like this.

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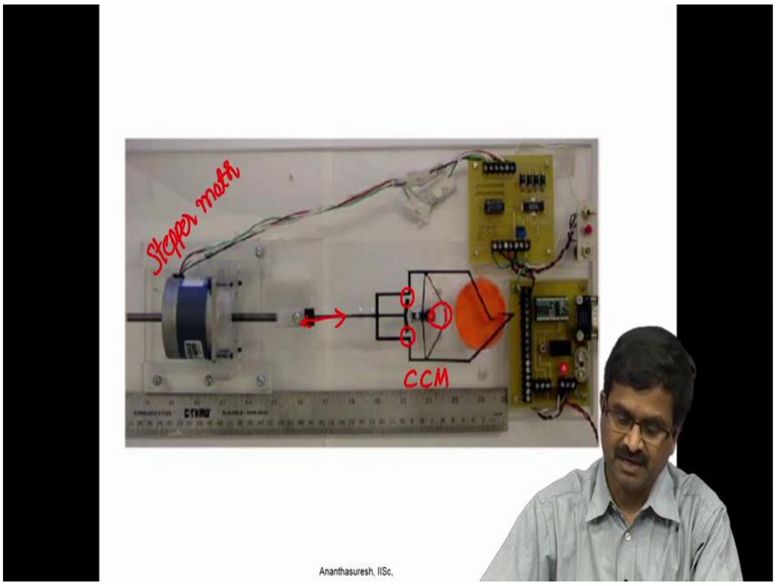

So, let us look up the device here is where the contact aided compliant mechanisms is; there is a stepper motor here; so which is going to pull this like that and then push it afterwards and here is where we have couple of points and they will be tracing a curve here these are electronics to control it again contact points or contacts in portion one there, one there symmetric and another one is over here.

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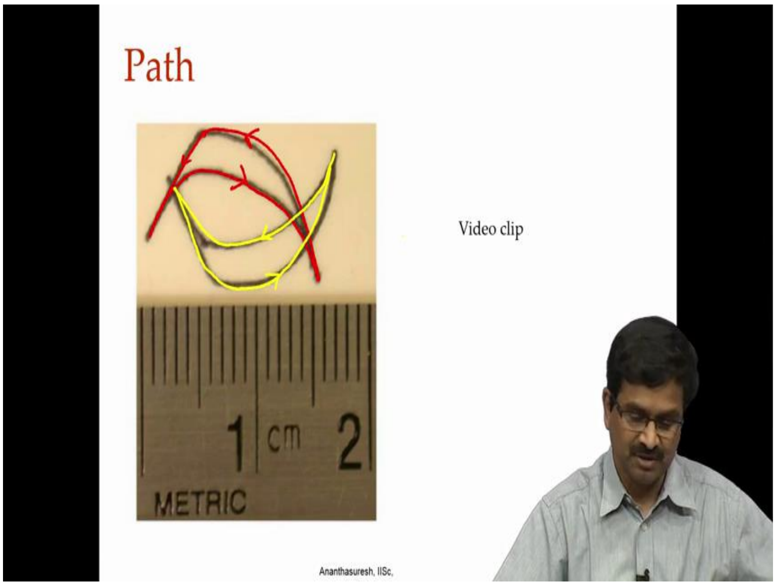

So, this surface and this surface will touch each other; that is what causes the change in direction and this stiffness. So, the paths actually in experiment they look like this, so in the simulation we had seen that goes that did not take into account viscoelasticity, what will happen is a point will start here will go like this and this is the non smooth point; it will go there and then while coming back it is different path because of in this case viscoelastic nature, it will go like this. So, we get enclosed paths like this, so the other one let me do with a different color.

So, it goes like this and then comes back like this; like a banana shape curve or chilly shaped curves. So, it is possible to get non smooth response even though you have smooth input; let us watch a video clip of this mechanism to understand what is happening here.

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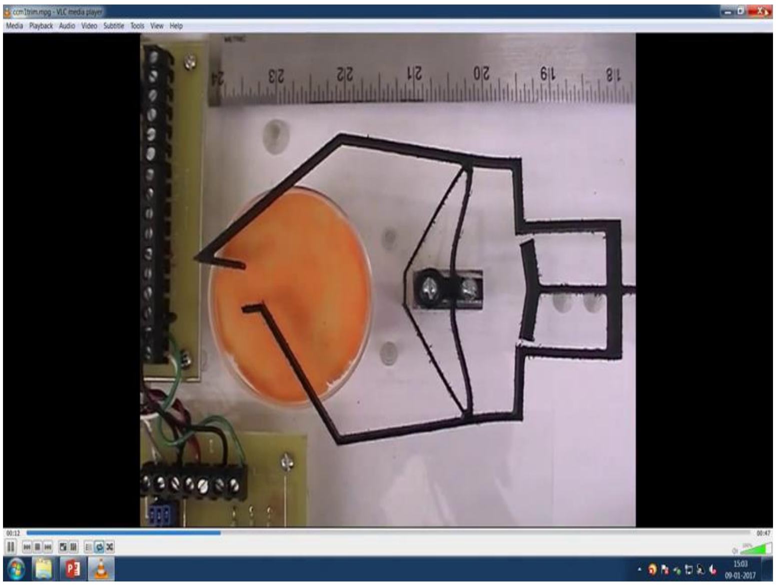

Let just see the video; here is the device of course, left and right switched and you can see where the contact where the arrow is and that contact happens their this non smooth behaviour begins and then soon after this contact also take place over here and they would have changed their path.

So, you have to focus these where the two pins are there they tracing this complicated path, now going back and then whenever the contact is lost then suddenly these things will change their direction. So, this is how you can get very complicated motion if you see this black one which is polypropylene available in black color. So, that has this single piece structure that is there are no joints in anywhere, it is just that there is intermediate contact over here over here and over here. So, that is the contact aided compliant mechanisms. Let us go back to the presentation.

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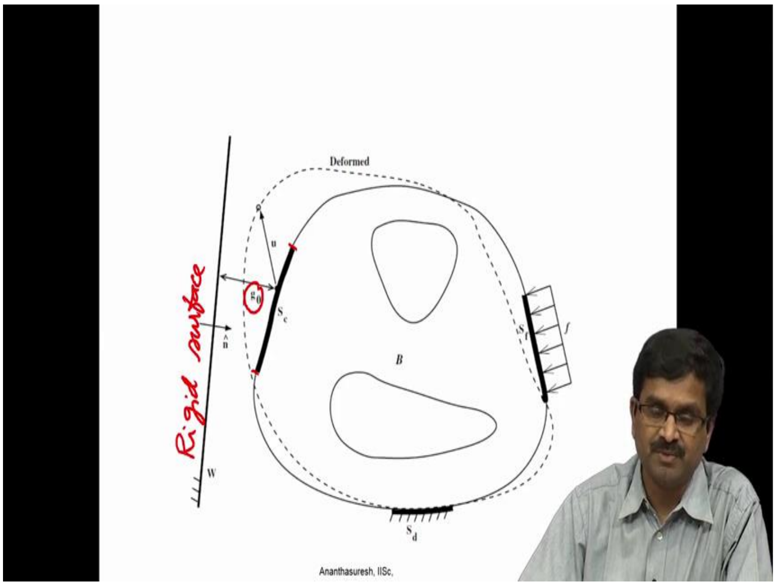

So, in general if you want to model it, so what we need to do is model the contact between potential portion of the compliant mechanisms, you need to know it ahead of time and a rigid surface. It can also be a flexible surface and it can be a self contact compliant mechanism can touch itself also; like it happened in the second and third contact, so it is actually self contact. So, over here this is self contact where are this is touching the rigid surface over there.

So, a self contact can happen or with the rigid surface and we should model that also by defining other potential function or springs that vary their stiffness based on the gap value; that is a new thing that was introduced here in synthesis that we have discussed earlier this contact modeling should also be included.

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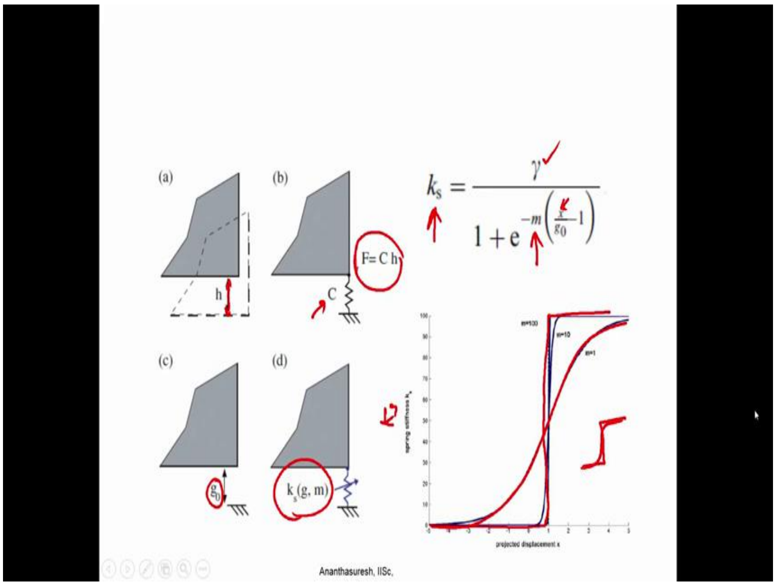

So, the way contact one of the ways, it can be handled is when you have a displacement boundary condition such as this a point as to go by certain distance; we can impose that by using some high stiffness infinite element analysis. Here what we do is based on the gap which is continuously changing; we can define a variable stiffness so that we can model the contact.

So, how is that variable stiffness defined? Here we have used this function gamma is some stiffness value 1 plus e raise to minus m times x by g naught; x is the displacement g naught then 1 minus 1. So, what will happen is this k s here can be made to vary like this, so here is a factor m as you increase the value of m it get closer and closer to this, but never be sharp like that it will always be somewhat smooth like this. So, you can use this in synthesis and design this contact aided compliant mechanisms.

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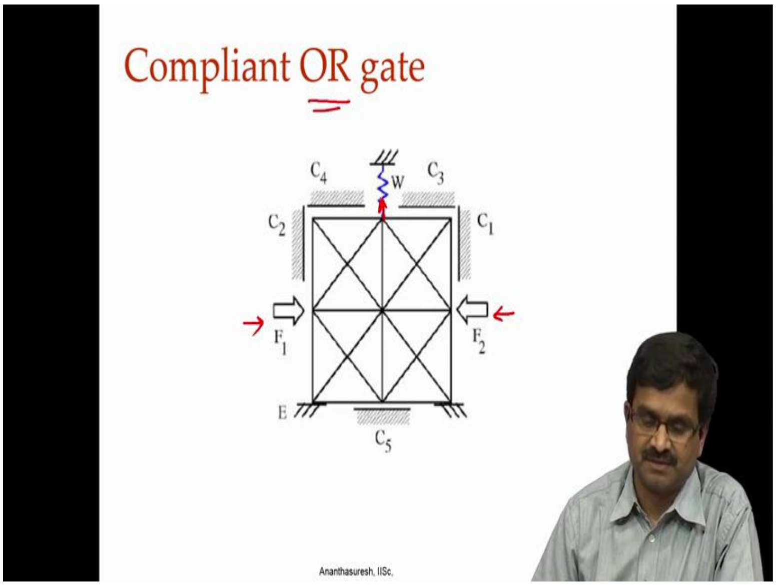

So, what can we do with that? So two things we discussed; one is tuning the stiffness other is getting the non smooth paths; in both cases non smoothness is important one even though the input is smooth.

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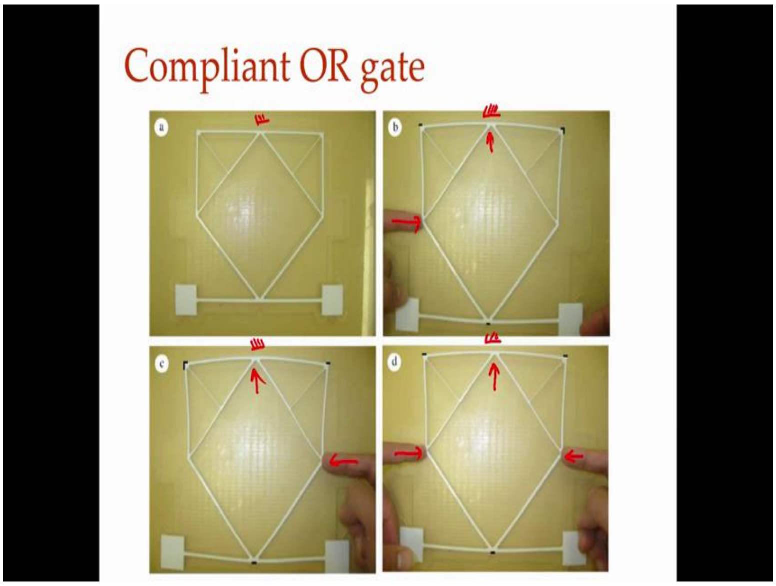

So, some examples is an OR gate and or the type of gate. So, what we want is that we want to solve a problem, whether you apply force 1 only or force 2 only or both are then together, we want this to grow up; that is what you want to design, it is an OR gate compliant or gate for fun there is no really application right now, but it could be there in the future we can make AND gate, OR gate, NAND gate and all the all the logic also can be done using compliant mechanisms.

So, whether you apply force 1 or force 2 separately alone or apply them together; you should get this and here is a design that was obtained using optimizations. So, here is the force and you see this is going up, here is the force it is going up and here is the force both ways it is going up. So, it is an or gate; we you can design those and what is the contact here, it is actually in terms of modeling that we had some force here when we are doing this. So, the gap there was a spring put in so that the stiffness was define which you do not see that kind of spring and without that we were not able to do because the point will move this way or that way, it had that contact put into this or here.

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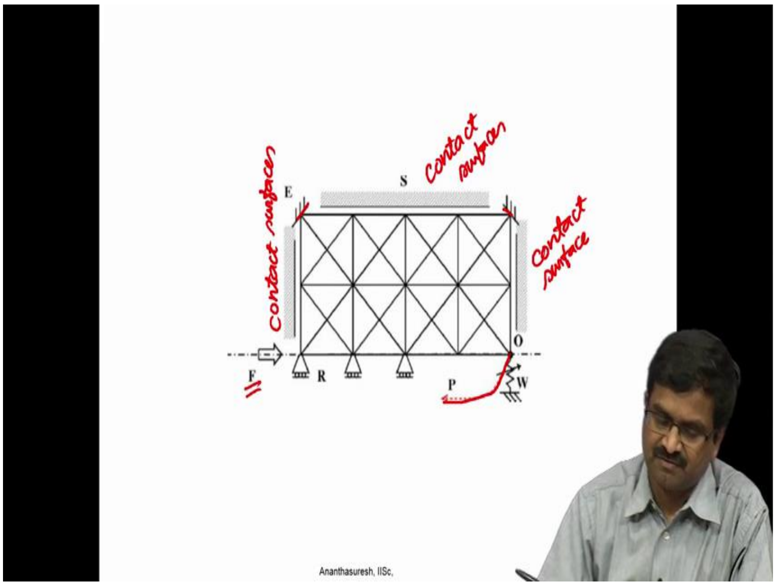

And here is another one where contact surface are actually defined, these are the contact potential contact surfaces we do not need to say that definitely contact should happen there, but you are saying this is generally fixed ones; those are fixed and there is force applied here; what we want here is a path that is somewhat like this. So, it should move down and then move this way in a sense that there should be a motion this way and that way. These are again potential contact surfaces. So that you can define potential contact surface here and there is of course, symmetry there.

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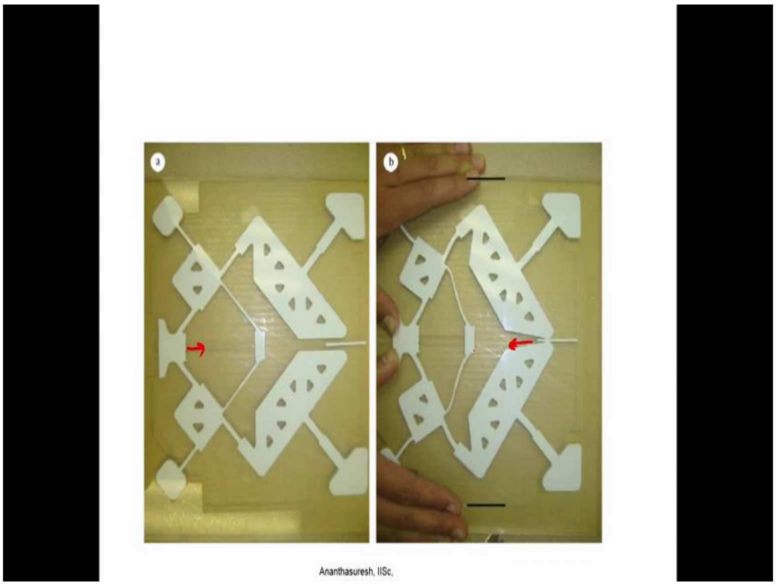

So, here is a is a design that was obtained, so when you have this, when we push on this I suppose, the force was in this direction when you push this thing will come and touch it and after wards it will move this way. So, if there is an object it will grab and then move it that way, so we get a design for this, so that was using contact modeling.

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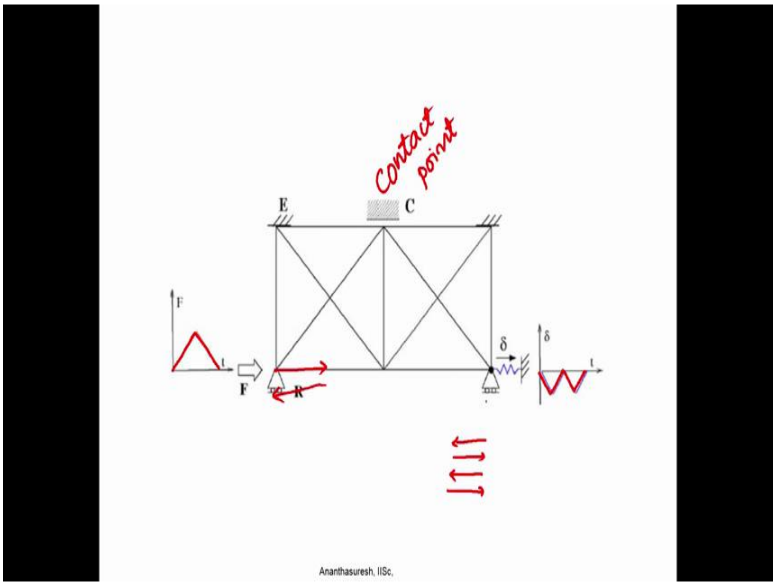

Here is one where the input makes one cycle, output makes two cycles which we had discussed in the context of signal processing like a frequency doubler, but it is a cycle doubler and that design of course, here is the potential contact surface. Here it is very specific I can (Refer Time: 19:51) call it contact point that is where initially we need to do this; this point is going to come back and then when you put more when it touches its start is coming back here, so it will move this way and then that way that will be one cycle of this from here to there.

Now, when this moves back then this will go back again and then come back, so it will be varies, so two cycles.

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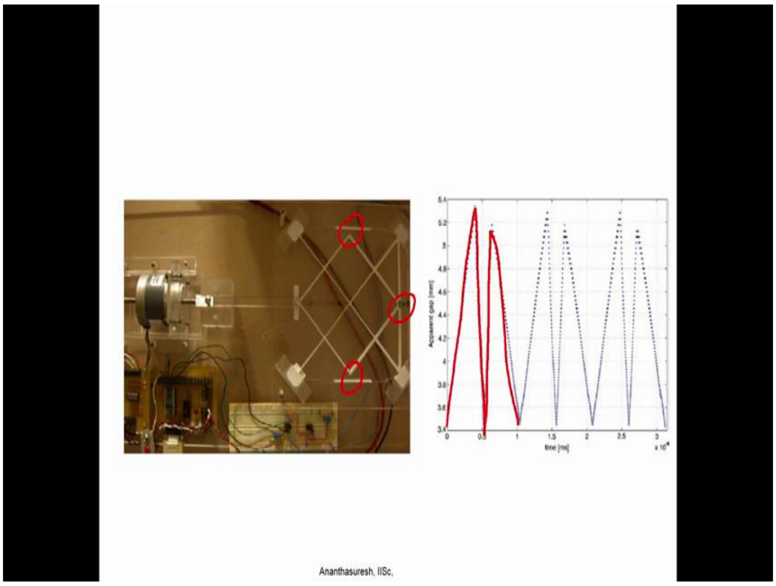

So, that was this contact aid compliant mechanisms, again this is the prototype where we have the potential contact surfaces there and this was to measure the displacement using the (Refer Time: 20:35) sensor you can see there is asymmetry. And so this one is did not exactly same as the second one that is because of various other factor that exist in mechanisms in particular viscoelasticity.

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Now, let move on to another concept which is called composite again emphasis it is not that compliant mechanisms are made of composite materials, but the mechanisms itself is a composite of two or more compliant mechanisms.

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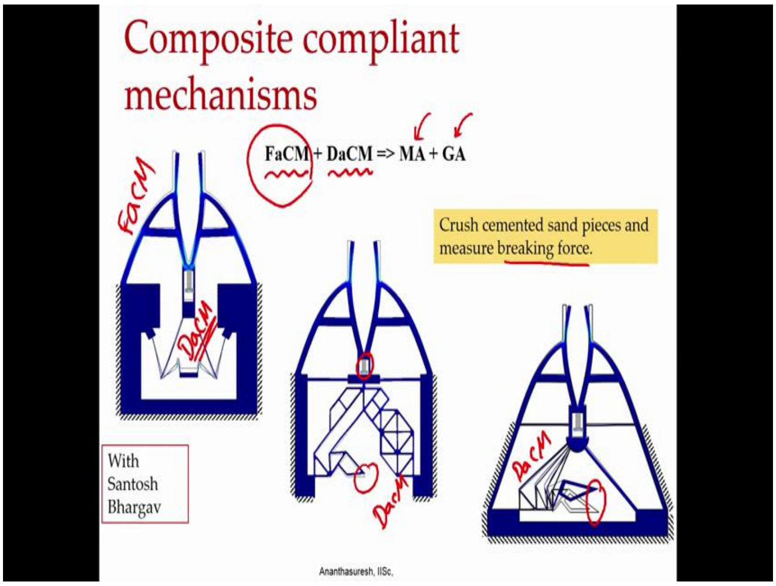

So, here we wanted to combine F force amplification compliant mechanism and it displace the amplification compliant mechanism into one, to get both mechanical advantage and geometric advantage a different places. This was to crush cemented sand pieces specimens in order to measure their breaking force.

So, the top one is the FaCM and this is DaCM there are different kinds and what happens is then apply the force, there is this specimen that is there; that will be crushed and how much our force is applied, we can see that in terms of the displacement here and measure by doing calculations what that breaking force is. So, here functionality voice, there are two different distinct functionalities; one is by hand we should be able to apply force and FaCM generates a lot more force to crush a symmetric sand specimen. Afterward in order to see how much force has been applied, we also have the DaCM.

So, these are all DaCMs displacement amplification compliant mechanism that shows you some displacement which you can measure visually or otherwise to know how much force we have applied. So, this is a new way of doing composite compliant mechanism to achieve some interesting functionality if there is a functionality that is more than one path, you can use two different mechanisms.

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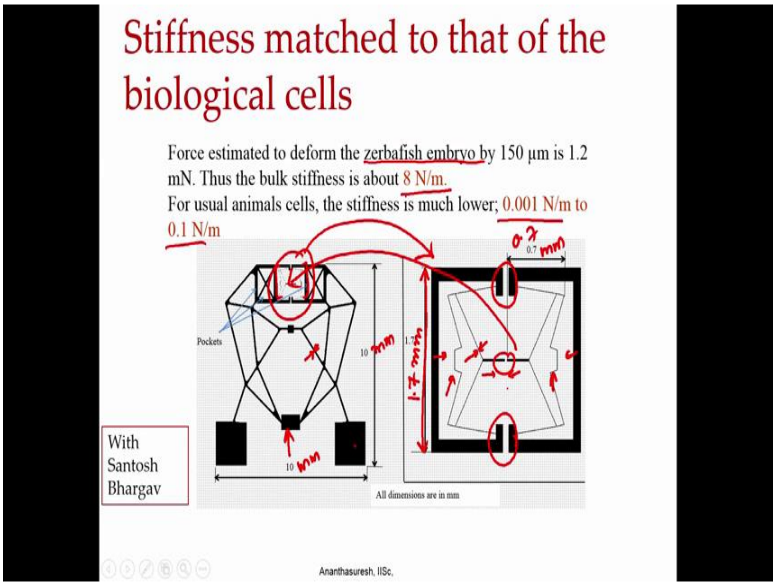

It is another one which is to make a mechanism, again there should be only one input here and we want to be able to grab biological cells or embryos; in this case bulk stiffness of zebrafish embryo is 8 Newton per meter that is very very small and for animals cells stiffness could be even this much smaller 0.1 Newton per meter or 0.001 Newton per meter, so how do you do. So, then your lithography will have limitation terms of what can be the width of that in fact what you see here which is only 0.7

millimeters; this is 0.7 millimeters, this is 1.7 millimeters from here to here and these beams are extremely narrow, there will be only fewer microns.

So, when you have that five microns can you make such a large device as 10 millimeter by 10 millimeters that is not possible with any process. So, here what we do is we have a mechanism inside there is another mechanisms. So, there is this and inside that this one is there; that is what you mean by composite.

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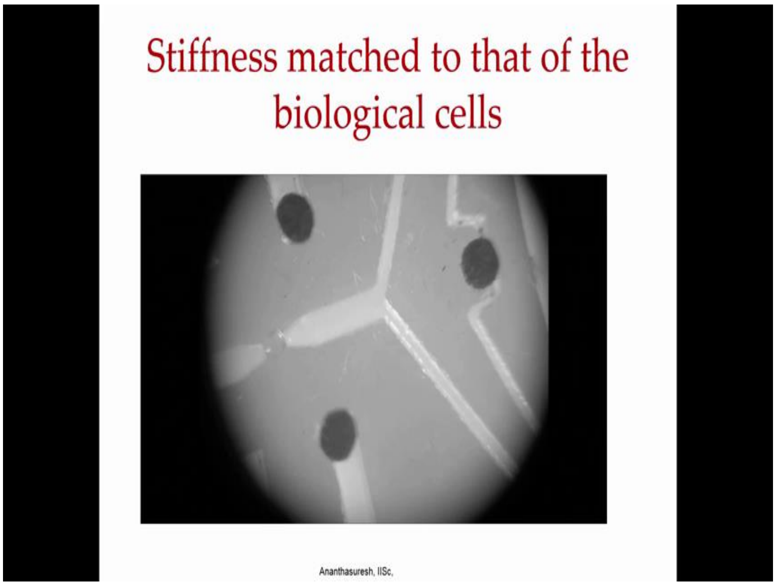

And that was done and we can actually see the zebrafish embryo, which is over their actually grasped under squeezed. So, it will come back it should it just you know you see that we just squeeze in that I will play again. So we can match the stiffness of the biological cell to that are the compliant mechanism by having a small one inside and big one; big one what is does here is when apply the force, it will bring this portion and this portion which is see here and here; it will bring them closer once they go there here is where our contact is happening again they touch is also a CCM.

When they touch then the force starts; this one starts going this way, this one will start going this way will grab the slide and likewise you can there is a DaCM here which will amplify the displacement there so you can measure the displacement and compute the forces, so a lot of things in one mechanism.

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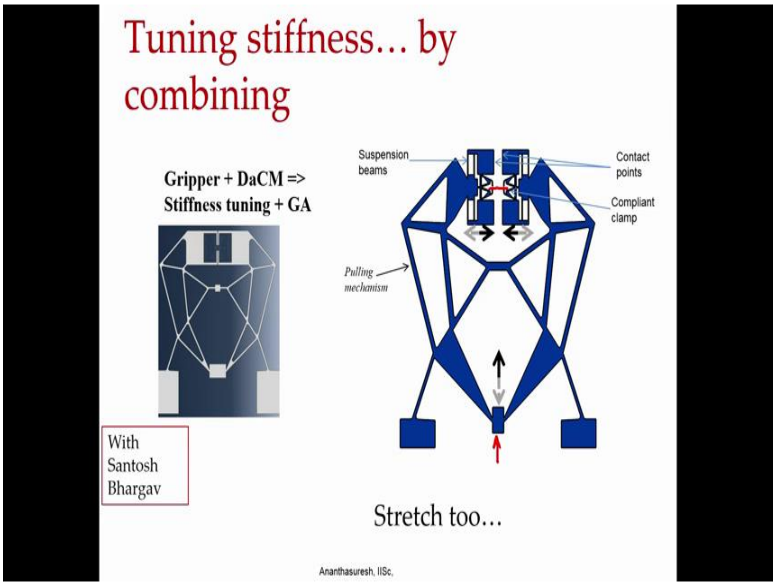

And the tuning the stiffness, we have one here where the same thing we apply the force like this; these things will come together when they touch these things open up here. So, when you put something over here, it will actually grab it and pull it. We will watch the video in again two different compliant mechanisms are combined together to make a composite mechanism; to tune this stiffness as well as get geometric amplification and manipulation (Refer Time: 26:00) stretching an object without attaching anything to it.

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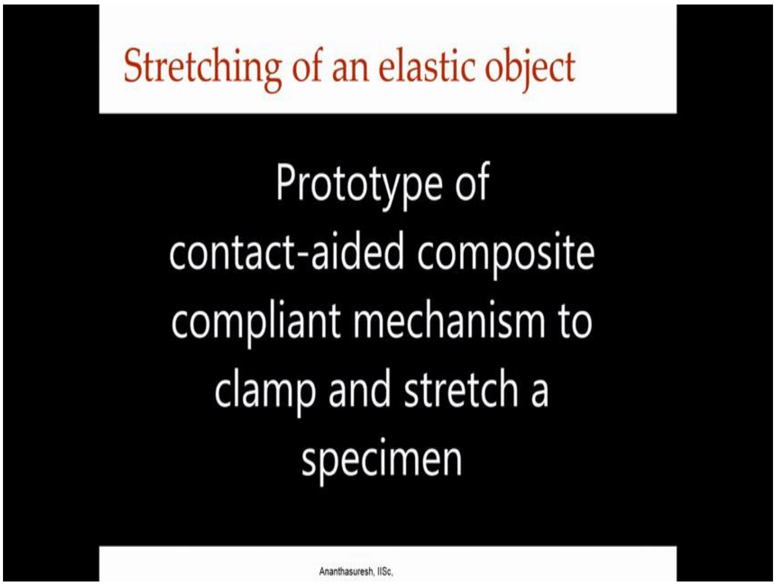

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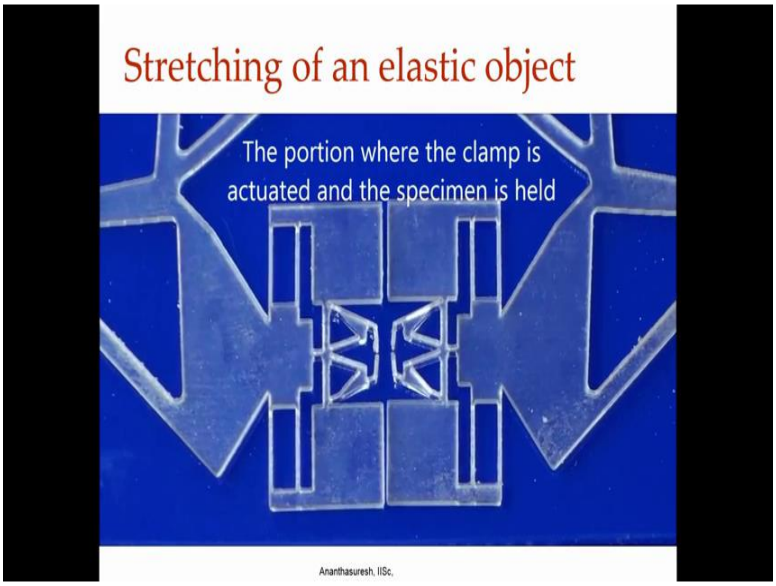

Let us watch this video, where we have this compliant mechanisms all single piece, we just push their continuous or smooth input; the touch over here and the open up and you can put a piece of rubber band as it will shown and when they open then it will grab and then stretch next time you press it.

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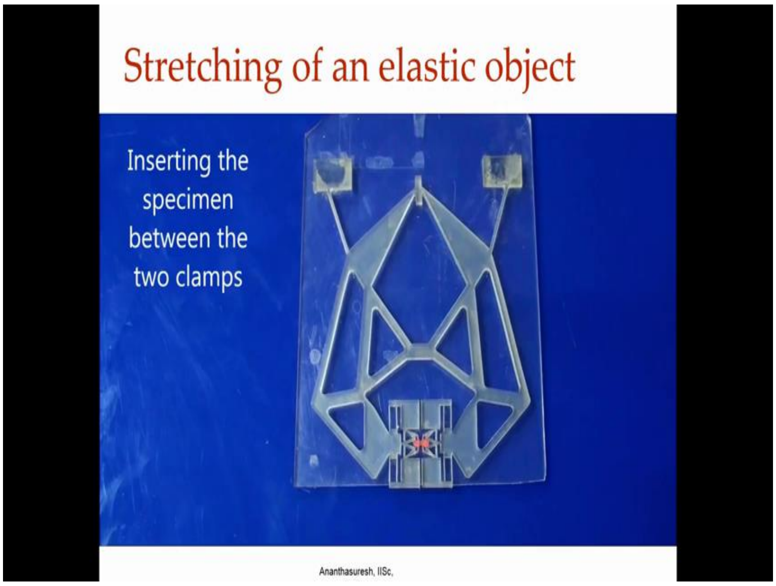

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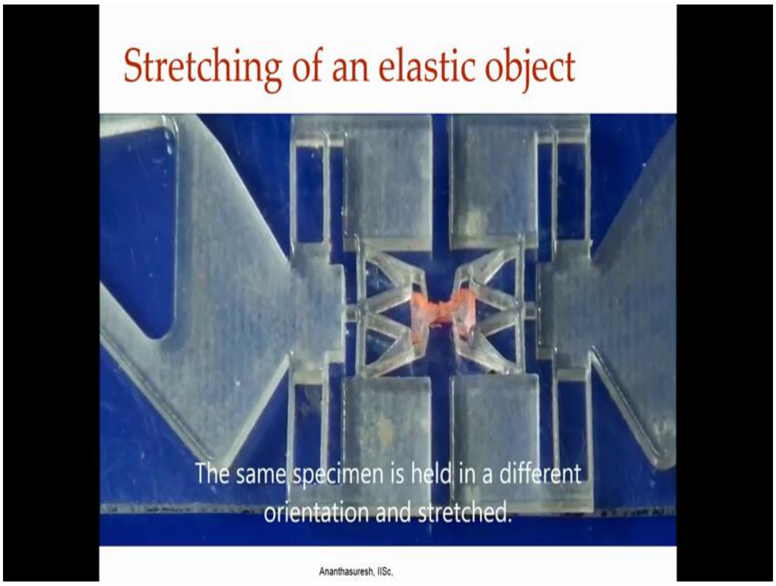

Now there opened, when they open you can leave a little piece of something what to want to stretch so this time it will be trapped when the touch. So, you have the little piece of rubber band and when it clamps and pulls, you can see in being pulled. So, you can actually pulled with a single peak that is what contact enables you here and also a mechanism inside another mechanism.

Now, let us suspend; spend a few minutes about anisotropy based compliant mechanism. So, far when we discussed design we wanted to get a number of segments beam segments arranged in a particular way in order to get the functionality that is what we did with several design methods. Now instead of that how about exploiting anisotropy this is something that is newly being explored in compliant mechanism.

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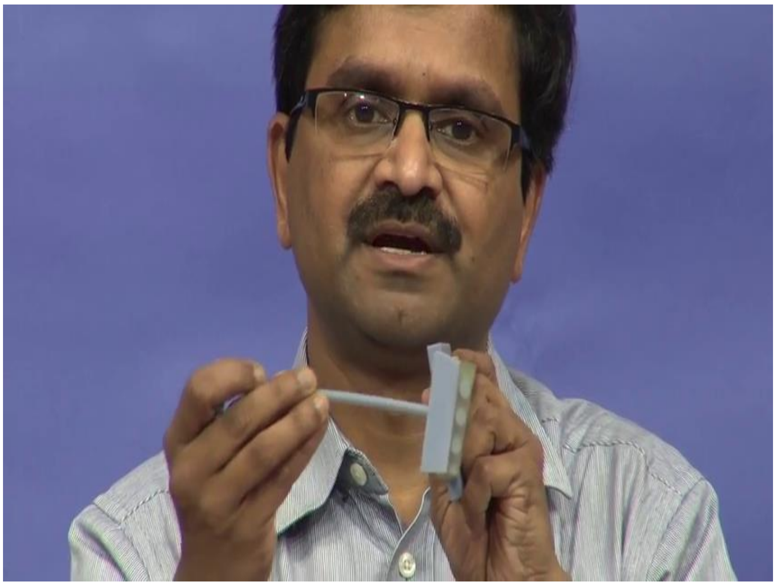

By that let me show an example of a block what I have here is a special block of course, is three D printed. So, you have basically a beam know like a wide beam, so normally when you have a beam and you apply force; you except it to only band. This particular one actually twists; if you want to see may be sides ways I put then apply force here, you can see it be twisted.

So, I am only applying force transverse force right you can see it very clearly or we twist I am not doing anything I am just pushing it here I am not doing anything at all. So, it actually twisting in addition to bending and that is happening because of anisotropy that exists in this one that is it is stiffness in the bending and twisting directions are adjusted basically what you have is a slab of course, is 3D printed, but imagine that you have made a material where you have a slab; that slab itself as anisotropy properties. In this particular case, the blue once you see rods they are all stiff material unburied into a flexible material which is the translucent material here, so because of that it is getting.

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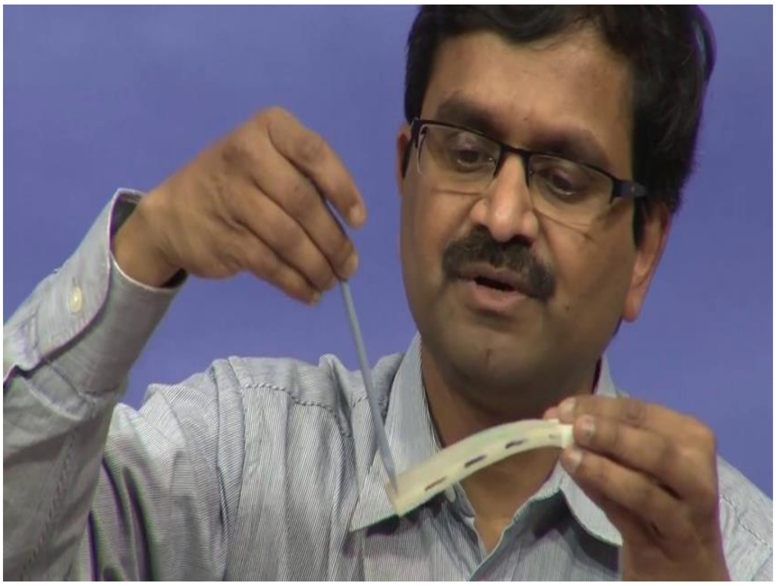

So, instead if I make another thing here, this is again you see some a sticks here, there are basically holes there; we have three D printed with one material with holes, this particular one when I do it, you do not see twisting; even though you have a same nature; the anisotropy is not dominant here. There is one more which has fiber like things printed into it, now if I apply a force there is a little bit twist, but you cannot see. So, if I keep it like this and apply you do not see that much you only see bending; there is no twisting like we saw with this other one, so this was very dramatically we could see the twisting.

So apply force, it actually see that it actually twist right; the whole thing is twisting like that we can see there are more rods here the few or rods here, so it as that.

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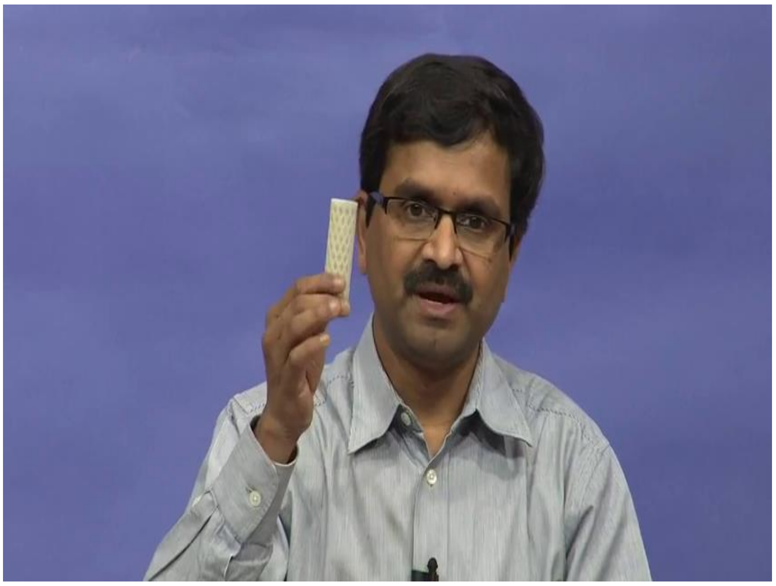

So, this particular one is what now people are exploiting to make cylinders like this. You have a cylinder and there is a fiber that is oven, this again three D printed for just to demonstrate, but this is what you know people are exploiting, let us look at a few examples of this.

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So, this is the reference for this shape shifting is; it is more of a popular sense optical written by Professor Sridhar Kota couple of years ago where he talks about some other things.

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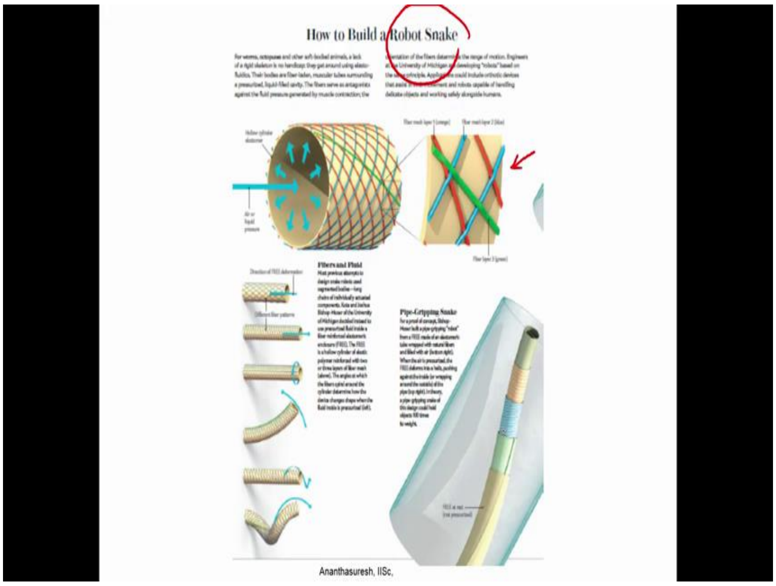

And this being pursued by few others, I will show you the references. So, what you have here if I have what I just showed you have oven fiber like this; there are three different fibers, three different colors it is shown there, but you can actually build what is called a robot snake, which is actually a compliant one. Basically you can see what happens, so it can stretch, it can twists, it can bend, it can do all kinds of things, it can do all of them together, so you can actually make things grow more like a Elephant trunk.

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And these idea, so we can have something straight; these are pictures taken from the article; it can bend, twist and you know do all kinds of things. What is the purpose of that, it is a different type of compliant design.

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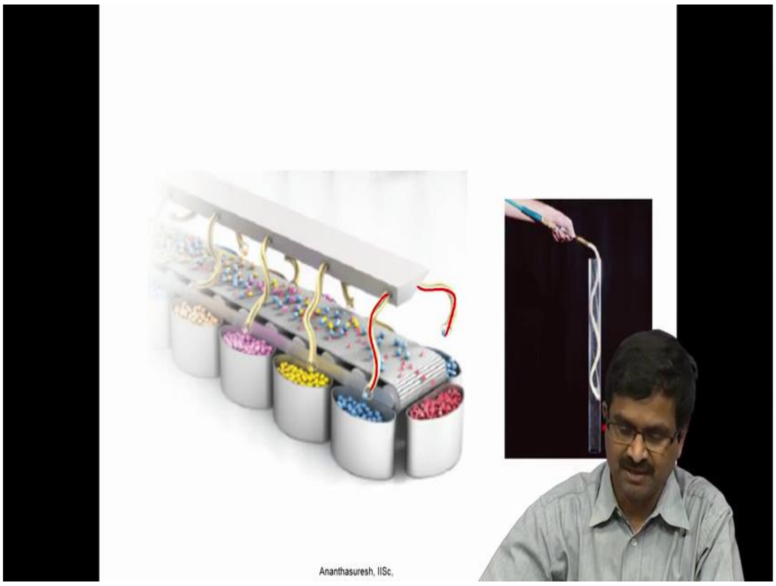

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So, you can duplicant place; let us say that they are all these snakes and they pick these balls and swart them (Refer Time: 31:18) place, it can grab things as I will show. So, it is basically you again want things to be flexible or compliant to do your job, but it is more like a robot because it is not for one particular function, but it is for several functions.

So instead of having a rigid thing like this, you are more like a elephant trunk that is going to do the job and that is what people are working on now and the interesting thing as you can see here is that; there is a glass tube here; inside that you put the snake, it actually grabs it so heavily that it can hold the weight of the thing there. So, you can actually pick up things like an elephant will rapid trunk around a log and then lift the log, so you can actually do this and this is real people are doing that.

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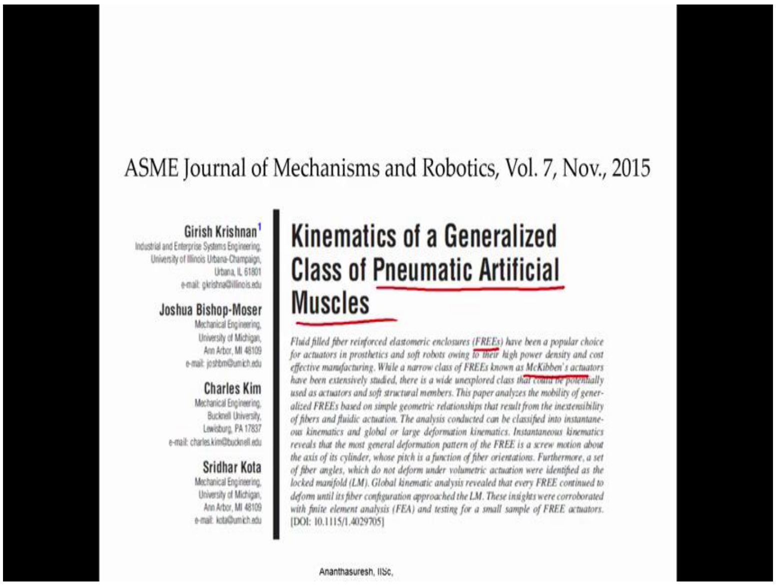

Here is a paper from ASME journal of mechanisms and robotics by Girish Krishnan (Refer Time: 32:14) in Sridhar Kota's group, where they talk about this pneumatic artificial muscles; this has been around for a long time actually something called McKibben's actuators as been around for a long time.

Now, they are exploring it; they call something called free fluid filled fiber reinforced elastomeric enclosure; that is a long thing they have put in acronym free that is not the point; the point is that you can make things that are all flexible and you can make them contract like this so here it is a long gated, now we can see it has moved so that is the movement.

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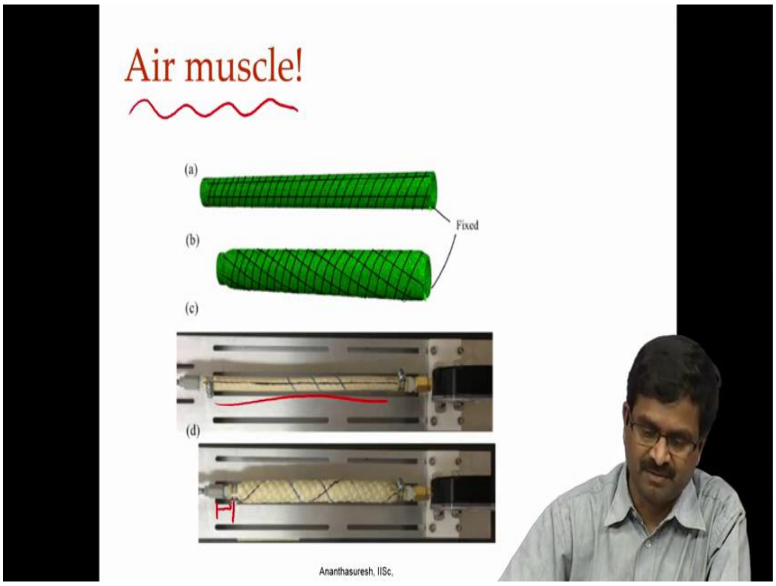

By just pressurizing it, so this is the McKibben's actuators what they call air muscle pneumatic, so air muscle.

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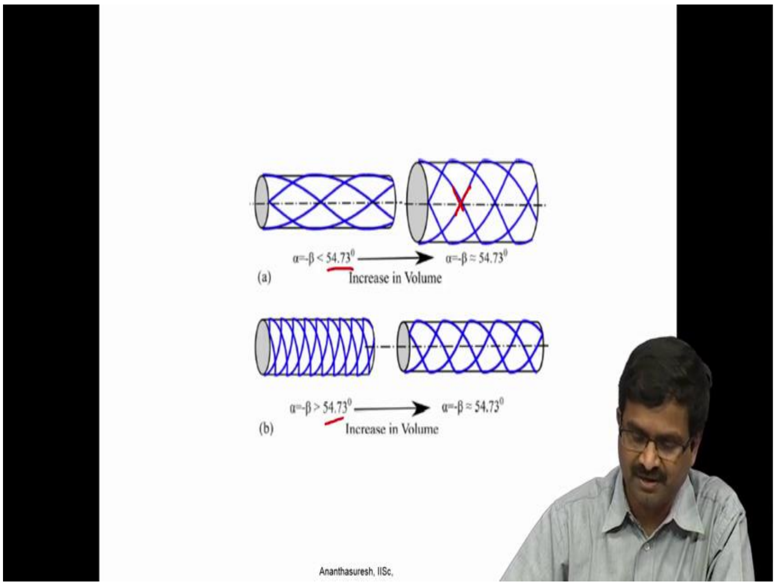

And there are you know this oven angles; this angle when it is greater than or less than 54.73 whether it will contract or expand is being shown here.

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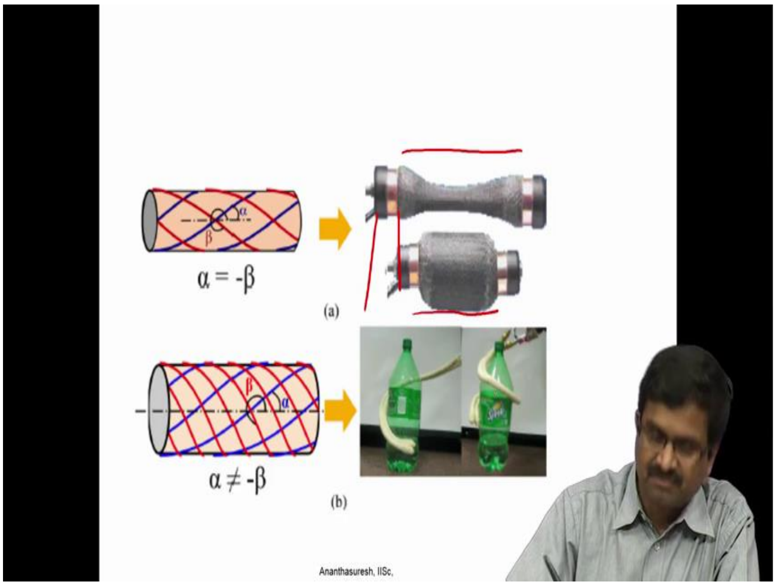

And this is the original thing when you pressurize it; it is going to contract like this, so there is an actuation. The other thing as I just showed, we can actually wrap it around things and pick them up and put somewhere else.

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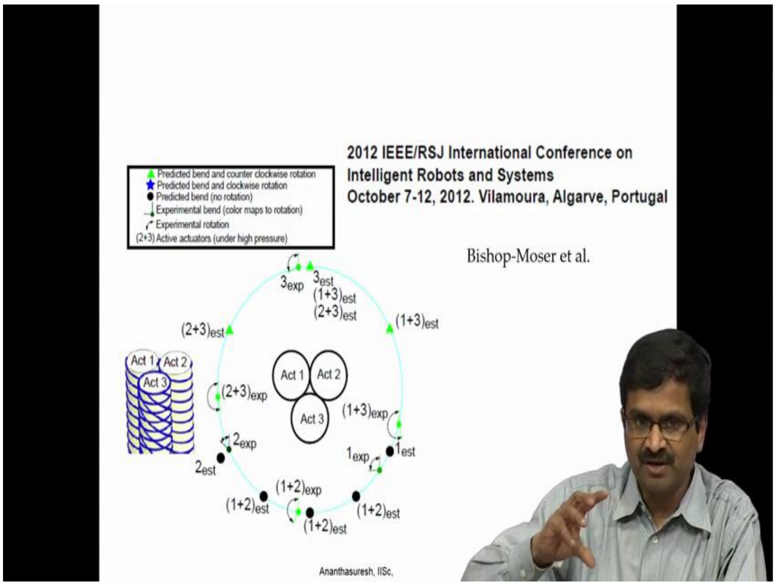

And you can put three of them and it is one of them bends or other one does not bend. So, you can get this helical motion that instead of having one as you send scientific (Refer Time: 33:38) article there are three of them. Each of them is pressurized differently, so you can get lot of twisting and bending motions, so you can actually make things that are flexible.

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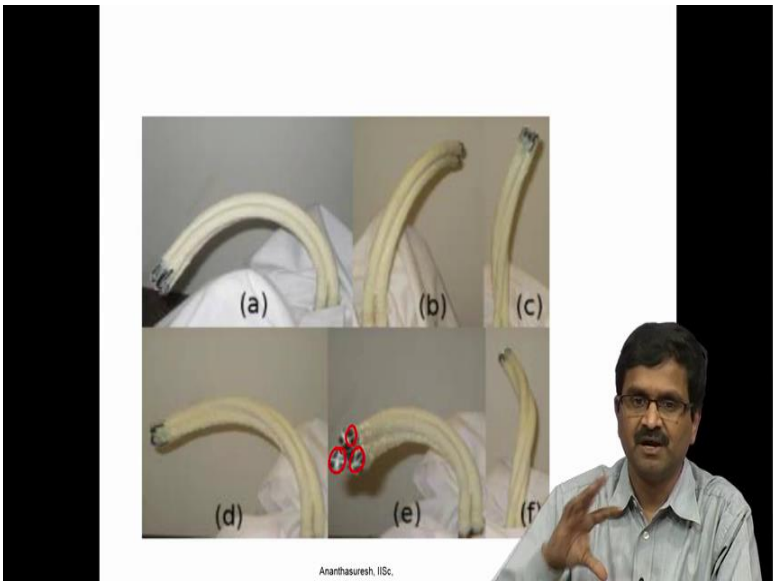

So, it is a new thing like this, so there are three things here like parallel motion they were like hydroid go here, they can walk they can do this. This is more of a robot concepts not necessarily a mechanism in a sense that with one thing with control, you can do lots of task; not that you have to design something for a specific purpose, but you can do this things. They are smart because of design and not there is any smart material, this is just fluid filled tubes, where you change the pressure and the bend twist and do what you want.

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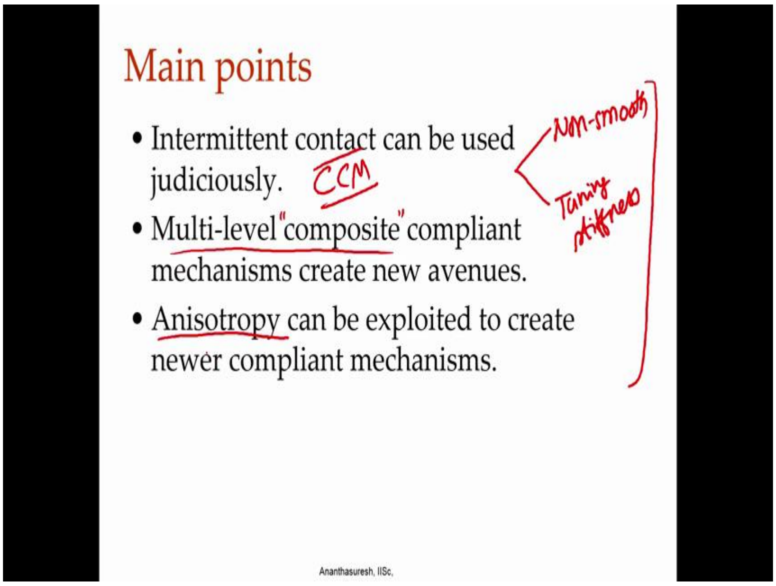

So, just to summarize what we discussed in this lecture, intermittent contact can be used judiciously for changing the stiffness or getting the non smooth paths. So, one is non smoothness that is something we discussed and other is tuning the stiffness that is changing the stiffness as needed, that is a contact aided compliant mechanism we talked about also called CCM, interesting CCM is increasing now whether we have done this work more than dozen years ago, now people are coming back to it and doing interesting things with it. The other is multi level composite again coat; uncoat composite is not composite material, it is just that we put two compliant mechanism together and show interesting behavior and how we can use anisotropy of the material, how do you put this fiber inside, how do you worry and them.

In fact, you can design the anisotropy, you can design a compliant mechanism geometry not be complicated; geometry is straight forward, but you make the material anisotropic and that anisotropy that you design computationally; you can get it using the fiber orientation of holes that you put and so forth. So, you can do it in two steps that is the next things, so that is you not depend on the geometry of the material to get topology this and that, it can be straight and anisotropy material will take care of it; like we showed that there is a slab when you apply transverse force it actually makes the things twist.

Similarly, we have made things where if we stretch something, it will twist that is the nature of the anisotropy of the material. So, we have discussed three new concepts and there are many more coming, some of them will have proper design techniques for them, some of them give you intuition to design new kinds of compliant mechanism; especially when you have anisotropy with air muscles. We can look at this compliant robots if you will that is also possible now.

Thank you.