**Compliant Mechanisms: Principles and Design**
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**Lecture –03**
**A glimpse of applications**

Hello, in the last two lectures, we got an overview of Compliant Mechanisms and also discussed what it means to have the spirit of compliant design in order to take advantage of various features that Compliant Mechanism possess. Today we will look at very important aspects, which is applications; whenever you do something different or something new people naturally ask what is the application; today's lecture is focused on application of Compliant Mechanisms.

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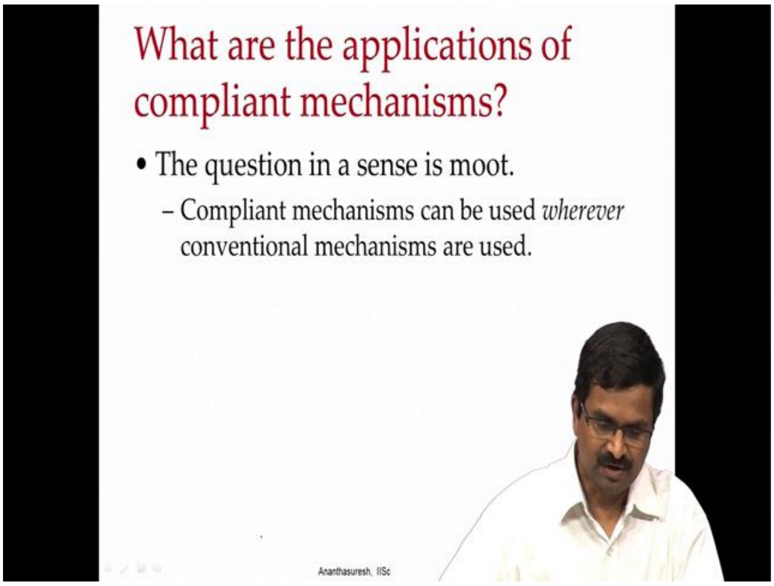


So, let us look at first the question what are the applications, I would say that the answer for this is rather moot in the sense that, whatever rigid body mechanisms can do Compliant Mechanisms can do that also. In other words, whatever applications that our rigid body mechanisms rather conventional mechanism have Compliant Mechanisms also are amenable for all those applications, in that sense asking specifically what are the application of Compliant Mechanisms as I said is in the sense a moot point you should not even ask that, but when you are learning about the Compliant Mechanism for first time, naturally; you want to know what the applications are, first thing that I would say is that, there are lot of applications in consumer products and I will show some of them now.

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So, you might have seen the shampoo bottle lids which are bistable.

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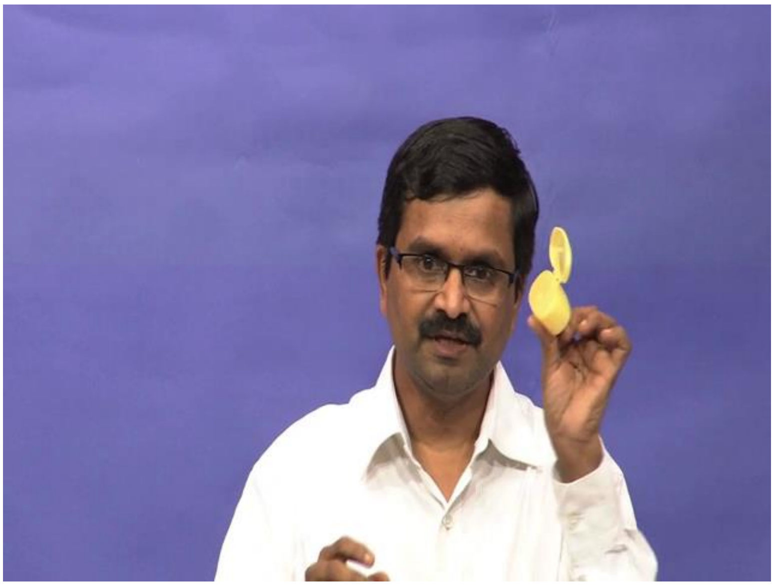

So, you can have this one, this is not really shampoo bottle some bottle this I think intensive care Vaseline does not matter, may plastic bottles today have this lids which are bistable so they go, either that position or this position and there is another snap fit here, which kind of closes it tightly and they are different versions.

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Here is another one which is really, head and shoulder shampoo bottle, which has this bistable very well pronounced. In fact, it makes noise when I switch from one state this is one state open state and that is the closed state.

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There are these bistable devices number of them and the here is, another one of the same kind in a different color now, this is I think Kissan ketchup bottle lid that also is bistable. So, there they have very interesting what I would call the 3 dimensional Compliant Mechanism what is sometimes called a butterfly hinge which has very thin shells, which have this bistable behavior. And, we had already seen example of the BRU jar, which actually closes the lid very tightly.

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And in another one which probably in India, which no so familiar it is a (Refer Time: 03:19) is a dental tooth pick cum a device with which you can do flossing that is between teeth. So, this has a very interesting behavior that there is, this segment which is very slack at the beginning the moment I press it here, it becomes tot. It becomes tot, you can put between teeth and clean. So, a number of these consumer products that exists in the market and they were all applications how they are designed, we have no idea because, that is usually not published in the literature technical or scientific literature, but these products are there, if we come back to the list of application that we have in the slides.

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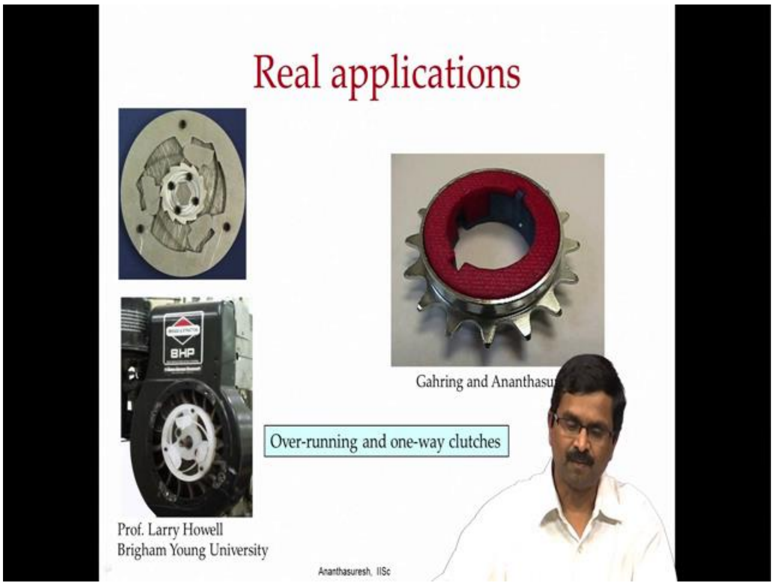


There are also lot of accessories in machinery and appliances, there are lot of Compliant Mechanisms there; here is one real application where Professor Larry Howell at Brigham Young University has applied it to put it into a Lon mover. Lon mover thick a better appliance or a device, and here is where the Compliant Mechanism is. It is an over running clutch the white one that you see, is the over running clutch that basically, depending on the speed either clutch will engage or not engage. So, that kind of a thing you can have plastic or with metal as well, what you see at the top, that is a real application.

Another one that one of my under graduates are done a long time ago is a bicycle one way clutch, if you ride a bicycle, if you ride forward pedal forward you go for forward right, and if you try to pedal backward then you stay put meaning that other time the torque from the pedals is not transferred to the chain; that means, your wheels. So, it is a one way clutch only one direction it transmits other direction does not transmit if you take apart one of those where I have the chains sprocket wheel still visible here, there will be many many parts. Instead of that, you can have basically 2 compliant pieces this is red color underneath there is a blue color and that basically has like a compliant fall or ratchet, which will make it go only in one way and not the other way in terms of transmitting the torque.

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So, these all real applications that even can use in appliances and devices, here is one more, that what we see on the right side is; what is going to Tweel from Michelin, Tweel is tire plus wheel. So, tire plus wheel is a (Refer Time: 06:05) over which becomes Tweel. So, Michelin had experimented with this concept, we do not see it in use now when I say it is a tubeless tire, it is basically tire itself acts like a tube or whatever function that tube a pneumatic tube does as you can see in this picture, this one looks like a flat tire, but actually it is not; it basically has a compliance in all around, this hub which takes all the shocks and acts like a Springer and a damper, but it is an interesting concept of compliant design, looking at this; some years ago one of my masters students Bhargav did this for a bicycle of course, as you can see here the spooks or whatever has been replaced with compliant segments here we retain the spooks because, when we start to imitate this it was becoming as expensive as a bicycle itself.

So, Bhargav came with a concept of putting something in any tire, tire of any size any bicycle there is no tube at all. There are tubeless tires, but they are still pneumatic, but here it is non pneumatic we just have one hoop in it which acts like a pneumatic tube to take all the shocks even though just like Michelin wheel, it looks like a flat tire, but it provides you the good ride that one wishes in a bicycle, and it can be retrofitted on at tire of any size and any bike any bicycle. So, it is also a real application.

And moving on to another application, let us look at precision mechanisms. Precision mechanisms have used compliant design or Compliant Mechanisms long before this field took this name, the reason for that is very clear, when you want precision in a mechanism in a machinery you want very précised motion that is; if we want it to move by 2.3 millimeters it has to move by 2.3 millimeters not a micron more not a micron less, if you use rigid body linkages it will be very difficult to do because, they have friction and also have backlash which we had discussed in a first lecture.

So, friction and backlash are not problems that are associated with Compliant Mechanisms, they do not have because, they are no rubbing parts and there is no lack time for engaging something only where we have joints and there is there are 2 surfaces which have to contact for the motion to ensue in Compliant Mechanisms when you use a fully Compliant Mechanism meaning the one that does not have any kinematic joints at all any kinematic pairs then it is void of the problem due to friction and backlash.

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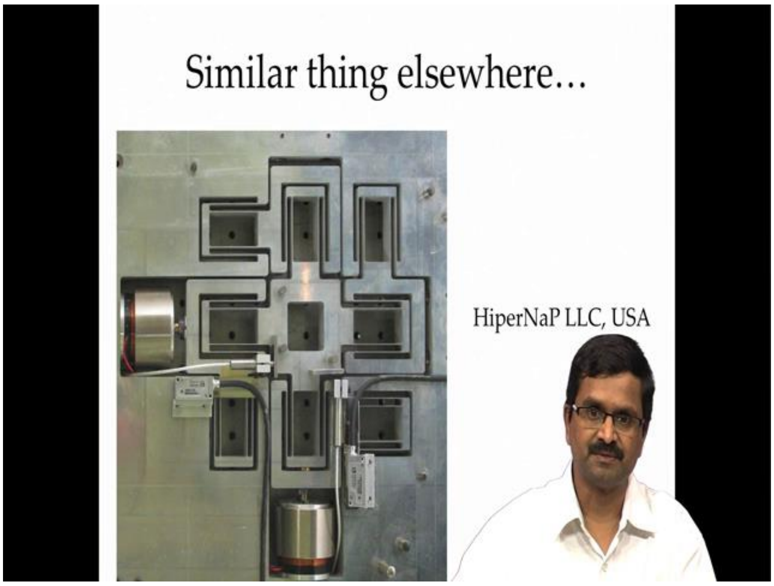


So, people have been using (Refer Time: 09:01) mechanisms here is an example, this is an x y stage which has lot of this beams each is the actually a representation or a compliant version of a sliding joint, we talked about sliding pairs, elastic pairs in the first lecture and here is one of those, they are arranged in a particular way 8 of them 1, 2,3, 4 5,6, 7, 8 around this x y stage it has 2 degrees of freedom, we will talk about degrees of freedom later, we have 2 motors, 2 actuators to move this in x y directions and it is really precise, if you have it is a good motor which normally people use what is called a voice call motor then we can have very precise almost nano metric precision we can get with this because, it is a Compliant Mechanism.

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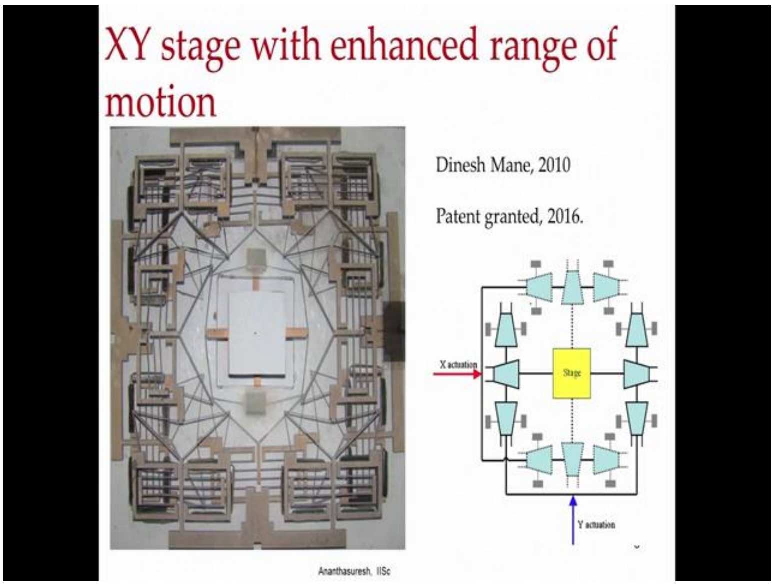


And there is another version of this, again it looks very complicated, but just like a previous one which decouples x and y motions here also it does de couple x and y motions in addition there is a block here, which is basically, a displacement amplifying Compliant Mechanism which you see here of course, there are 2 layers there is a we want to put in a single layer the previous one had 8 blocks let us go back and look at it as already counted 1, 2, 3 in the top row and then 2 in the middle and then 3 in the bottom row, these things are arranged if you look at this one, if this is upright this is upright this is upright this is upright, so, 1, 2, 3, 4 are upright and these are 90 degrees turned 1, 2, 3 half of them. When you arrange them in this particular configuration you de coupled x y degrees of freedom even though it is all made of one piece.

Now, if you want to amplify the motion of the actuator wherever it moves you want a longer range for the stage then unit have a different configuration which is the one that shown here, you have the central stage and then there are 12 building blocks each of them identical they have a DACM and a compliant suspension, this particular thing shows a sliding joints and a displace amplifying Compliant Mechanism when you arrange them in this particular fashion 12 of them you get this or you can arrange them 6 in each plain and attach at the stage you can get this mechanism. This also will be suitable for precision motion along with enhanced range. So, there are application precision machinery lot of them are there, like I said these were in existence even before Compliant Mechanisms field took shape in late 1980's in early 1990's.

Now, let us move on to another very interesting application which is micro nano systems at very small scales assembling is a big problem is not like you cannot do it, but if you do it the advantage of micro systems especially what is known as micro electro mechanical systems field there if you have a process that involves assembling a cost of the device is going to be very high, and in fact, MEMS are inexpensive mainly because, and in a single wafer you can make a number devices without having to assemble part by part. The moment you have something that has joints even though fabrication process is do allow fabrication of joints without actually assembling, but a process becomes expensive once again people do not want that, because MEMS like electronics had to be really cheap. So, using Compliant Mechanisms makes a lot of sense and that is what people have doing, people are been doing without even thinking, it is like very natural for using Compliant Mechanism in micro and nano scales devices and systems.

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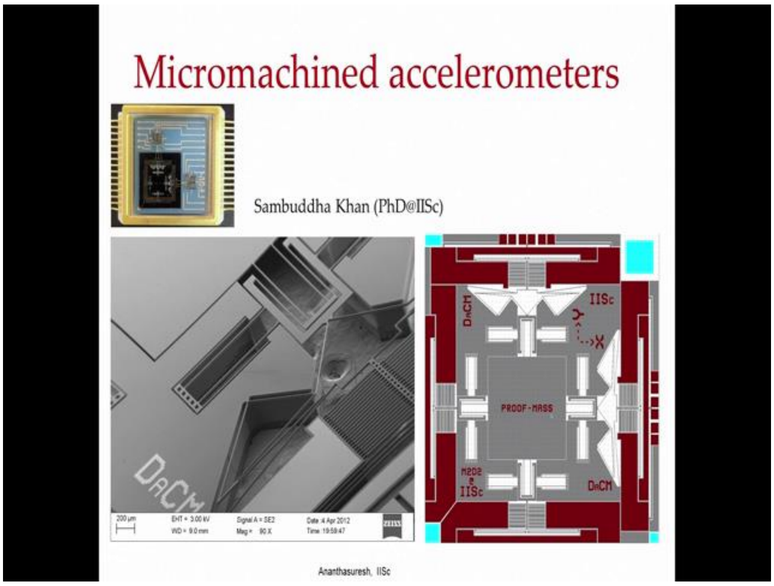


Here is one such device, that one of my former PhD student Sambuddha Khan has done, which is what is shown here is the packaged Micromachined Accelerometers for 2 axis I am showing this because, it uses exactly the stage that I just showed in the impression mechanism application. So, we have the proof mass here moving the mass is not one rather acceleration will cause the mass to move you can measure the displacement using let us say capacitance, here you see a lot of capacitance comb fingers over here. Instead of that, if you put DACM that is we have that thing here, he is a proof mass is all that arrangement of 12 building blocks I talked about in a single plane 1, 2, 3, 4, 5, 6, 7, 8, 9 10, 11, 12 again if it is horizontal, this is vertical, this is horizontal and then we have this version of the DACM.

And this going to give you lot more displacement of their sensing comb fingers as oppose to be displaced the proof mass, and it is all done you can see the silicon scanning electron micro graph here, and the width of this beams is typically 5 microns are as small as the fabrication process allows and the Compliant Mechanisms beams you see here very tiny and there is assembly involved. So, you can have complicated mechanisms Compliant Mechanisms made using photo lithography.

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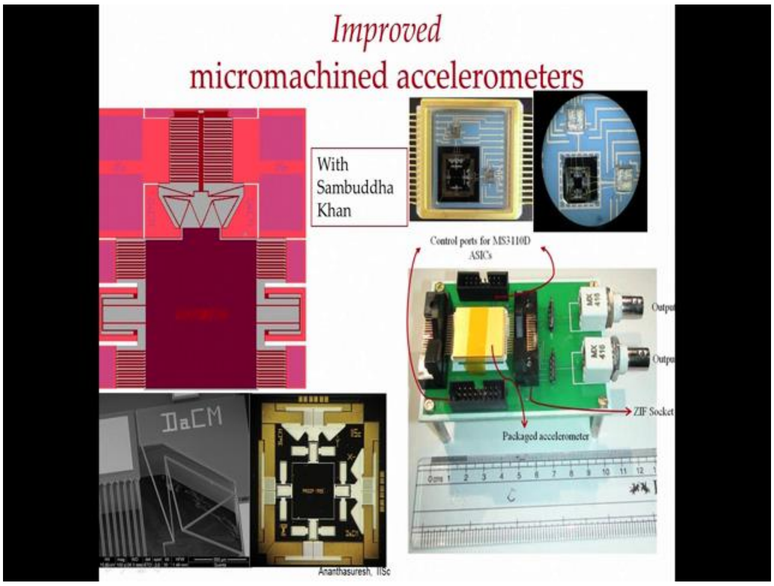


Here is a single axis accelerometer, shown that was a 2 axis here, we have single axis in corresponding scanning electron micro graph here which again you can see compliant nicely made here, it just looks like the graphical compare graphic image that you see there and it is a 2 axis 1 the chip that goes in this part it is magnified and showed here is a packaged one. When you do this, you get we have I put this thing call improved, what does it improve here, it improves both resolution or sensitivity as well as bandwidth

bandwidth meaning for what frequency range this accelerometer is going to work as it is intended and here usually in accelerometers there will be a trade of between sensitivity and resolution and bandwidth because, sensitivity is m over k proportional to mass divided by spring constant whereas, resonance frequency which is relate to bandwidth is k over m.

So, they have trade of between if you achieve one you have to comprise the other, but when we use this Compliant Mechanism DaCM here, you do not have to make the compromise it really gives you a improved thing and here again, the crucial one is the Compliant Mechanism suspensions are one and DaCM is another.

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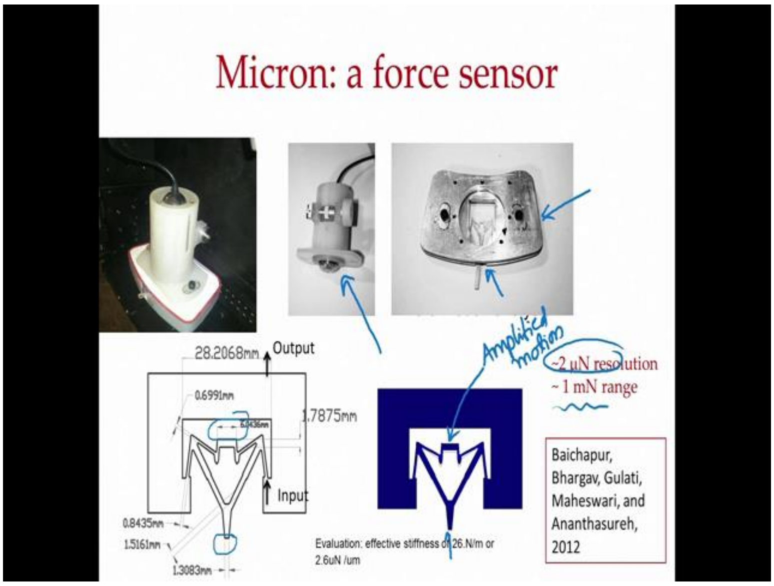


And looking at another sensor it is not really micro small although it can be made micro small as well is meso scale, you see the device here is if you look at the dimension here, will be about centimeter size. So, this particular width from here to here is 6 millimeters if, this middle one is 6 millimeters let me draw it. So, this thing here is 6 millimeters you can imagine the other one will be couple of centimeters this way or that way. Here you have a probe, this is the probe and if you apply a force here this if there is a force that comes like this, there will be amplified motion here which can be picked up with a digital microscope.

Digital microscopes are quite inexpensive these days and digital microscope looks at this you can do image processing and get with this device a resolution of 2 Micro Newtons.

Look at the size of the device is in centimeters you can actually resolve 2 Micro Newtons over a range of about 1 milli Newton. And you see this aluminum casing and the mechanism can be just inserted like a cartridge and this has this capability of measuring micro Newton which is,, quite uncommon in commercial devices because there are excellent force sensors up to about milli Newton or 0.1 milli Newton and then much lower nano Newton femto Newtons there are lot of advanced force microscopy techniques that are available, but in between there is neglected region and Compliant Mechanisms here fill that gap.

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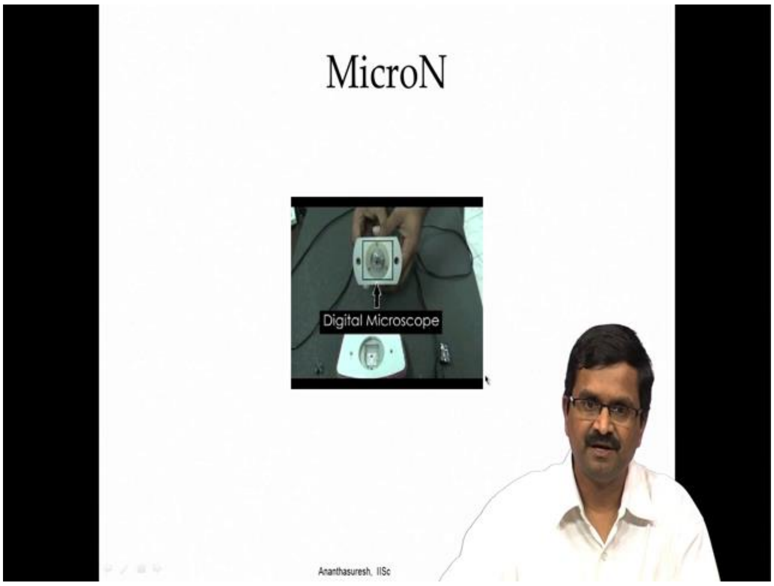


And here is a small movie that let me just play that. So, we can see what this has it just shows 1 minute video of how this micro Newton force sensor based on a Compliant Mechanism works, this was when in our lab and my student Gauthami is actually showing that he does not have anything other than a Compliant Mechanism and this digital microscope over here, that looks at a and of course, comes a USB drive and you connect to a computer it does connected to a program which gives you the ability as will show experiment.

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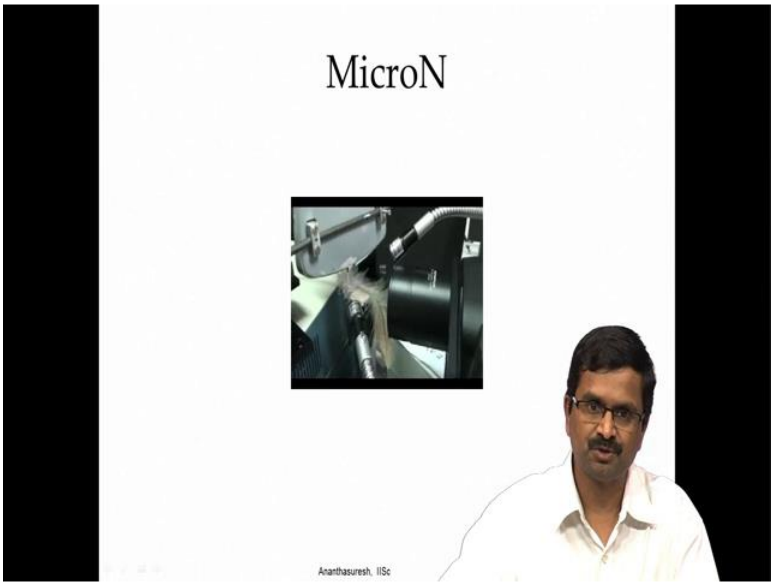


If we take a feather and touch it you do not feel a force that micro Newton force our fingers cannot feel, but the sensor was tested to show that when you have this after feathers which are called downy barbs, when you touch them and move with this probe that are touched with Compliant Mechanism, that shows this image it is moving ever so little which shows the mechanism given reading which you see how much force there is.

Moving on to another application which is smart material based systems many other smart materials are so called active materials, especially; let us say piezoelectric one it can give you a lot of force when the stroke is small. In fact, most of the piezoelectric material when they are stags or otherwise compare to force that they can deliver displacement is quite limited. So, you need a mechanism to convert that large force and small displacement to large displacement against some smaller load.

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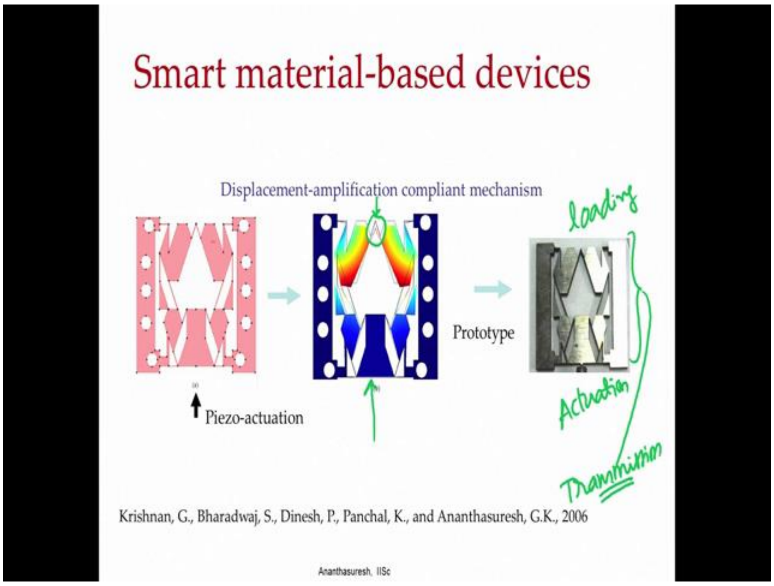


And one such application that we had worked on a number of people worked on using Compliant Mechanisms for piezoelectric materials electro (Refer Time: 19:51) materials and (Refer Time: 19:52) materials and n number of others the idea here is, let us say I want a device to be operated with piezoelectric actuation which gives very small displacement, in order of let us say few microns and there will be enough force that you can use that force as you can see in the compliant middle figure here this movement you hardly see whereas, here you see what was there has moved from there to here, it is able to retract when apply the force here that is also inversions that is we look at what is happening here let me draw this. So, here is where the pier active is pushing and it is coming down, but quite a lot if you see, it can amplify displacement. So, this is one version that was made with metal again emphasized any material can be used for making Compliant Mechanisms here it was done with aluminum or spring steal where you can apply piezoelectric actuation there and this moves almost by a millimeters by taking a 25 microns stroke for the piezoelectric actuator.

So, smart material base devices need a Compliant Mechanisms as transmissions in automotive like, cars you have engine and then transmission and then you have tires or wheels where it give in turns the wheel. So, here also between actuator and the load which will be on this side, this is the loading site, and this is the loading this is the actuation in between you have what we can call transmission. So, this thing is transmission.

So, Compliant Mechanisms can act like transmissions for smart materials based devices there are a number of applications related to this and Professor Mary Fraker at Penn State University has pursued this angle quite a bit in her work. Let us look at aerospace applications, again there are number of applications in each category I am showing only 1 or 2 examples just to tell you what are the application areas.

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Aerospace one of the very interesting applications that we had mentioned probably in the first lecture as well is to have this Adaptive Compliant Wings what are called Shape Morphing Wings, because the aerofoil shape is optimal aerofoil shape is going to be different and in different conditions of the aircraft let us say while taking off or (Refer Time: 22:39) landing there will be different airfoils and normally people use this flaps, there are hinges basically instead of that you can have something as it is shown over here, it naturally just curves this way or that way and gives you the right profile everywhere not just a flaps here the entire shape of the airfoil can be changed.

It is a big application because, even a small change in a shape can effect overall efficiency fuel efficiency of the air craft, because small changes in this particular case create very large effect on the overall lift and drag on the air craft wings. And these are really huge devices these Compliant Mechanisms what you see here is an aircraft where normal wings are not adapt your compliant wings, but the compliant wing is actually over here, this is for the testing purpose is only for testing while flowing, but now these are been moved to real wings that is from being underneath after all the wind tunnel test instead of doing this you can do it right here by putting this devices and these applications also in wind mill blades weeping on the wind conditions a directions of wind you can change the airfoil. So, that you gain a lot from the power generator.

So, the real interesting operation shape morphing there are many other things in aerospace components.

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Here is a version of that there is a company called FlexSys, I think it is F l e x Sys you can look at that website to see how this compliant wing changes it is airfoil shape as per the needs when you give an actuation inside, wings are actually is not much that much room there towards the especially towards the tip, but there is where you need the deformation that can be done with compliant (Refer Time: 24:42) inside this.

Moving on to another area which is Biomedical, there are lots and lots of applications here let us say surgical tools there are number of applications where you want to gain avoid joints in things that go inside the body because, if you have that if you have joints in between there could be lot of bacteria, virus everything can get stuck sterilization becomes the problem, if you do not have joints sterilization becomes easy nothing gets stuck, because there are there are no small narrow spaces for things to get stuck.

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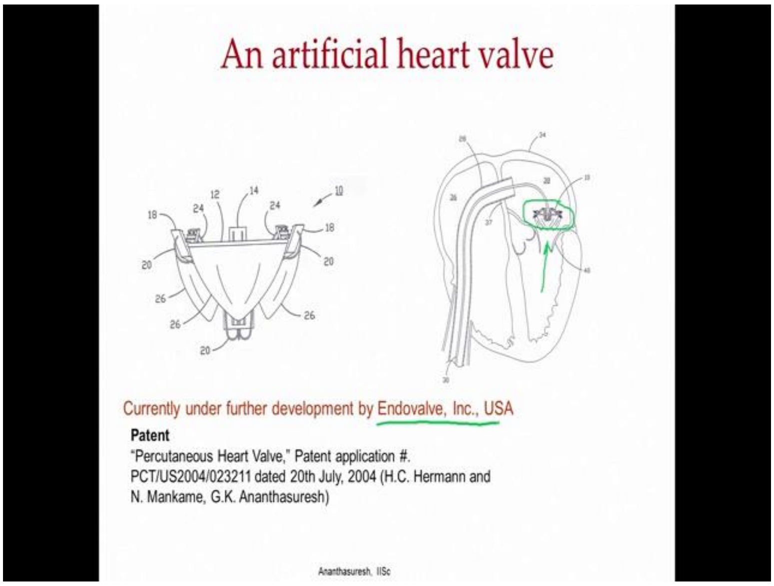


So, Biomedical devices have lot of applications in surgical tools and lot of biosensors as well there are also actuators, here is an example of a valve replacement compliant device which is a defective valve in the heart such as here, you want to insert a new valve and put it in place and that can be done. In fact, a company has adopted this technology Endovalve, you can look at the company website the name might have changed now, but still if you go to that Endovalve did they activate a new company which is still marketing this.

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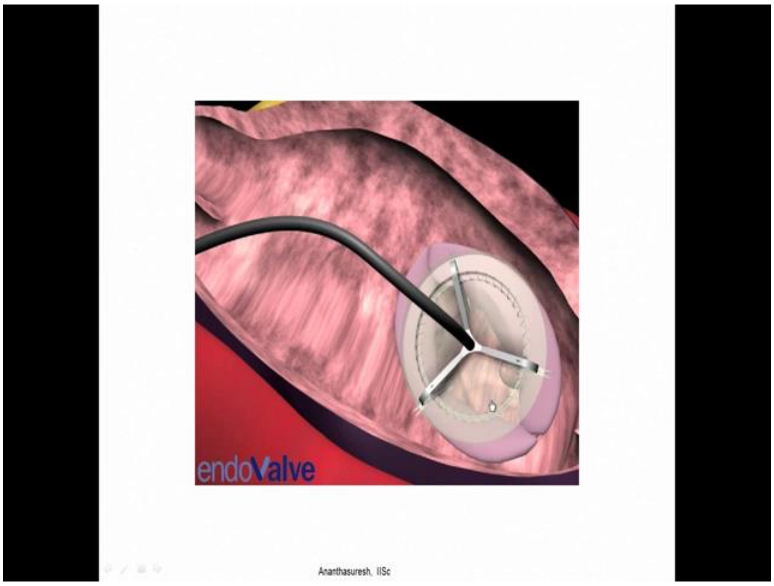

This particular one I will show a small video of that you can see how a Compliant Mechanism can be used to deploy a valve which is (Refer Time: 26:15) inside a catheter, so it has to be a very small tube that goes into the heart replace that. So, into that the compliant which is completely (Refer Time: 26:23) in into this tube it will be inserted once, it goes into the heart it deploys like umbrella and then place it what the doctor with whom we have worked has said was doctor Herrmann Howard he said that, sometimes they place it and they want to take it back if it is not positioned right.

So, it had to have three states of completely closed in like this and then opened it puts there and then it goes into state where you can actually place it and change it back if you want, if it is not positioned properly. In this video you only see that being placed, you can see the Compliant Mechanism all these beam that are bending. So, that is the beauty of Compliant Mechanism where you can make tiny devices that have complex functionality such as, this one. Biomedical devices there are many more applications than what I am presenting now.

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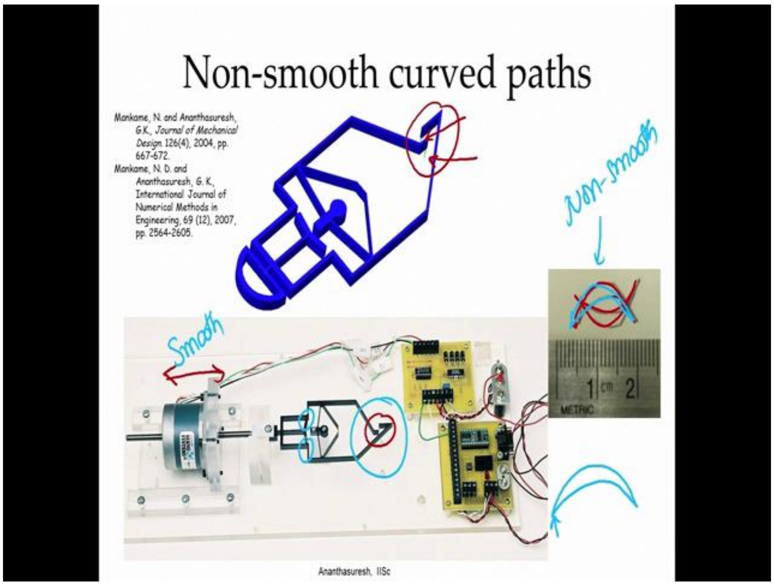


Here is one for tissue cutting there are 2 needles let me get the pen there are 2 needles here there is one over there, another one whose tip we do not see 2 needles in this position it is a planar mechanism basically needles are over there. And you have one actuate over here that goes back and forth it is a stepper motor here it can be any actuator when this goes back and forth these tips here will trace a complex path like this, and this one goes like that there are 2 paths let me change the color for the second one there is one path other path goes like this and this way, there are 2 paths like this here.

So, how are they achieving this even though the input here is smooth, the output that you see that this things will undergo is non-smooth meaning, they have non-differentiable point there is a cust it comes like this and suddenly changes direction and goes back like that. So, over here there is this cust that changes direction that happens because, there is contact happening here and here.

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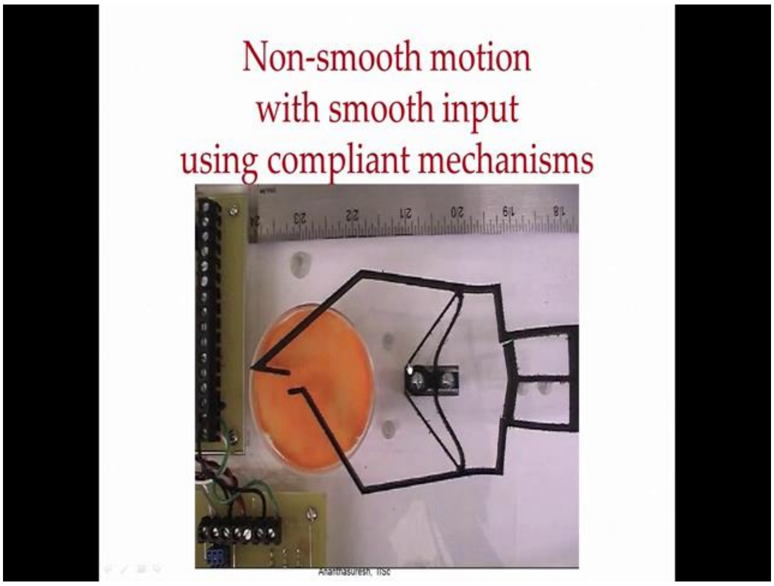


So, let us watch a video movie for this and all we are doing is moving this back and forth I should not have touched it. So, let us play this video. So, you have these 2 things moving and here it is only going back and forth, the movement contact happens here and here as well as here that is where it changes the direction of the path by repeatedly doing this if there are to be the cell or tissue you can cut it out. So, you can do it very fast this is intentionally played very slow, if you do it fast it will cut in a same place repeatedly for sharp needles it can tease the tissue out. So, you can say these are the tissue I want to cut. So, it can just take it out in the laboratory applications or even real surgery. So, you can get complex motion out of Compliant Mechanisms and you can even suture with these things.

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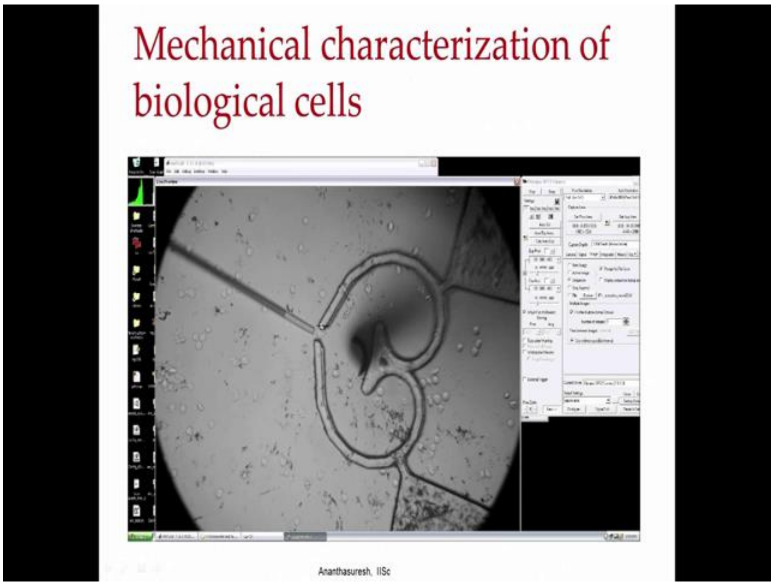


Here is another application in biomedical area where I have to get the arrow now. So, the biological cell, here it is a MCF 7 breast cancer cell which will only be 10 microns or 12 microns in diameter and that is being grasped with a Compliant Mechanism which you see when it comes into focus you can actually see it being slightly squeezed while this tube is looking on the tube is only to position it; it is a pipe at which you can push and pull and position it there the idea is that you can do mechanical characterization of biological cells. And automotive applications are too many that are not even showing, there are lot of little parts in the cars and motor bikes and trucks and other things. So or even railways there are lot of little devices which can use Compliant Mechanisms I will show something in the area of robotics.

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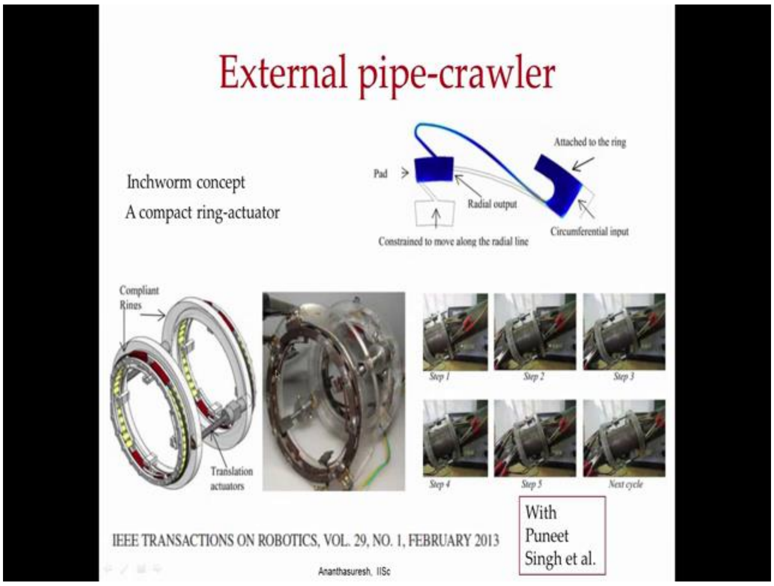


Again showing one of our works where we had designed an external pipe crawling device where there are bundle of pipes imagine under the thickness of each pipe has to be monitored the pipes are so close, that you have to have very compact device that cross on the outside of the pipes not inside. Let us say has a corrosive fluid and you want to monitor the thickness of the pipes it has to ride on the pipe these one of those that was designed with shape (Refer Time: 31:20) actuation in that what was interesting was, there was a circumferential input that causes the radial output for this to hug the pipe or release and so it can go like monkey, the 2 rings here when this is holding this is free it can move and once this becomes tight this loosens and this spring will bring it back like in to your motion like a monkey would climb a tree coconut tree and that is how this works and this used the active materials smart material (Refer Time: 31:54) and very compact Compliant Mechanism made of spring steel.

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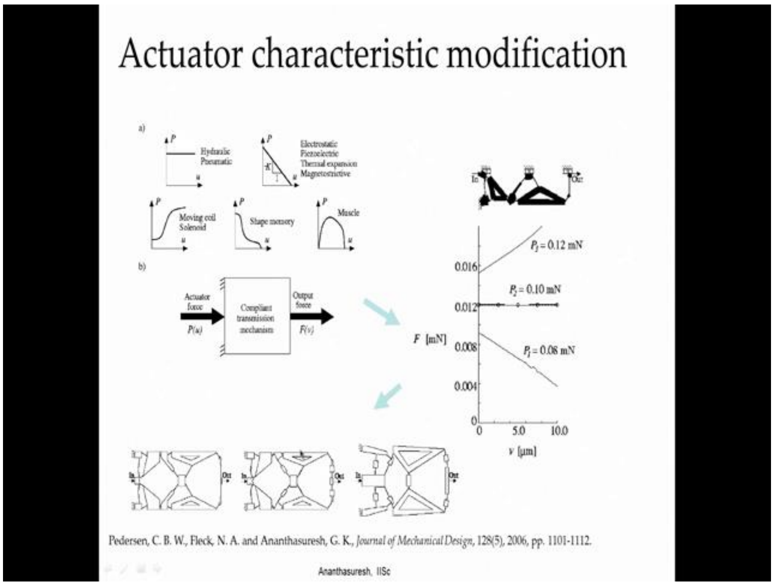


So, in robotics there are lots of other applications or transmission, here is an example where you have an actuator with certain characteristic. It could be hydraulic or pneumatic in which case it will be just flat with respect to the stroke whereas, electro static piezoelectric all this actuations are active or smart actuations would deliver less force as a stroke increases, but if you want to get hydraulic pneumatic type you can use Compliant Mechanism as a transmission and try to get something like a flat response, that is force will be constant with respect to other stroke and you can use mechanisms such as this, that is another applications.

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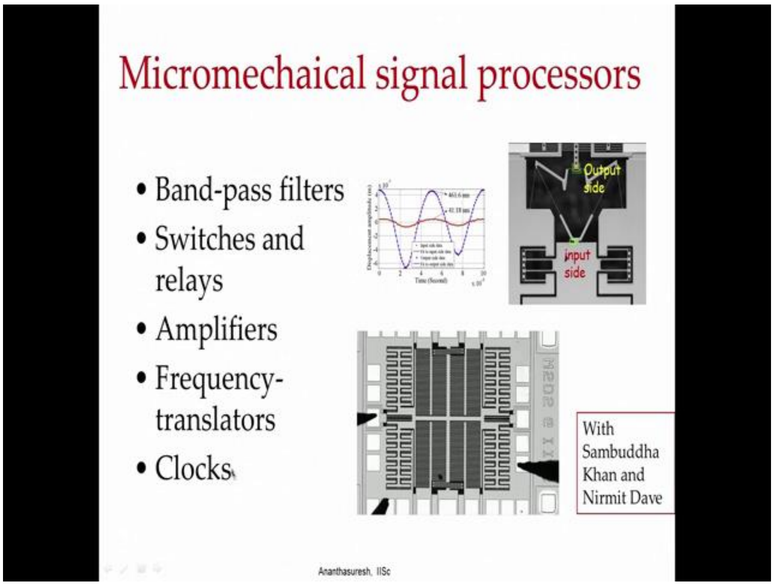

There are many many more applications of Compliant Mechanisms and you can look up the slides there is no need to explain all of that, here you can have micromechanical signal processes you can use band pass filtering, switches, relays, frequency translators, even clocks using Compliant Mechanisms. Just to recap our application areas are very vast and we only looked at one or two examples, from each applications area and there are many more application areas again wanted to remember is that whatever rigid body linkages are conventional mechanisms can do Compliant Mechanisms can also do that job.

Thank you.