Complaint Mechanisms: Principles and Design
Prof. G. K. Ananthasuresh
Department of Mechanical Engineering
Indian Institute of Science, Bangalore

Lecture – 01
Overview

Hello, this is the first lecture on Compliant Mechanisms; the course title is Compliant Mechanisms Principles and Design. In this lecture will have an overview of complaint mechanisms to see what they are what the concept is and so forth.

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Let us begin by looking at a few complaint mechanisms that my group at Indian Institute of Science works on; has been working for several years; what you see here are compliant mechanisms at several sizes Macro that is very large and Micro that is very small of the other of the microns as in Micro systems or Micro Electromechanical systems and then in between there is also Meso that is let us say hundreds of microns to a few centimetres that is what we can call at a Meso scale, between Macro and Micro and then also the nanoscale for which I have shown to (Refer Time: 01:18) which are also in a way complaint mechanisms that you will appreciate once we understand what they are.

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In this lecture we will have an overview and there is a subtitle to complaint mechanisms which it says is Motion without Hinges and Sliders and that summarises what complaint mechanisms are without having joint such as Hinges and Sliders and other types; we can have mechanisms that do exactly same thing as the conventional mechanisms would do.

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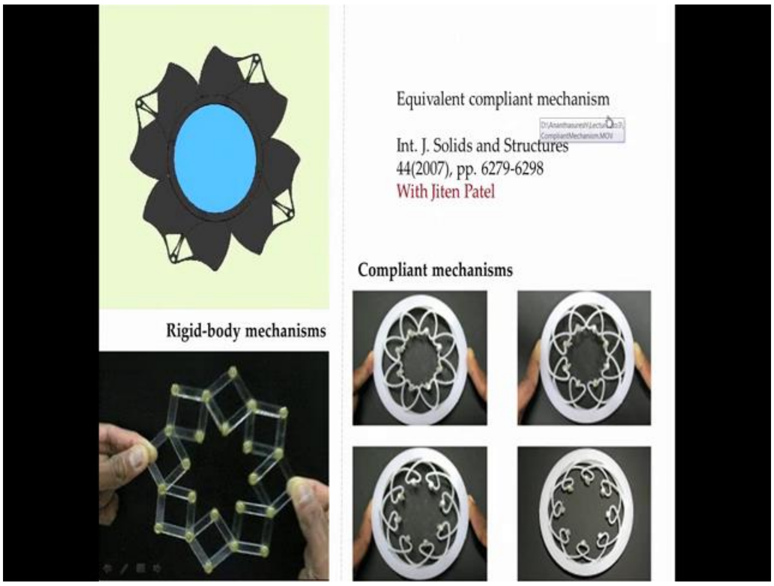

Let us look at couple of conventional mechanisms; the one that you see here is has let me see this one get out of this arrow. So, if you turned something here circumferentially it is moving radially in and out as this mechanisms shows and mechanisms intrinsically are very beautiful as you can see here one can have it on a circle or window to open and close or you can look at this hobarment linkage, which again takes this outward motion over here to inward motion along the radial direction for these things.

So, the circle grows bigger and smaller as you move whereas, here we are turning right you can see these circles moving like that. So, there is circumferential motion these are all the mechanisms that have rigid bodies and joints that is why we call them Rigid Body mechanisms. As oppose to that you can have complaint mechanisms which are shown here whatever these two mechanisms do they can do without having any joints. In fact, here there are a few joints, but they can also be removed if you were to use the dimensional machining of this polypropylene device here. We will learn more about this in a case study much later in the course. So, you can have an Equivalent Complaint Mechanism for any rigid body linkage that you can come across.

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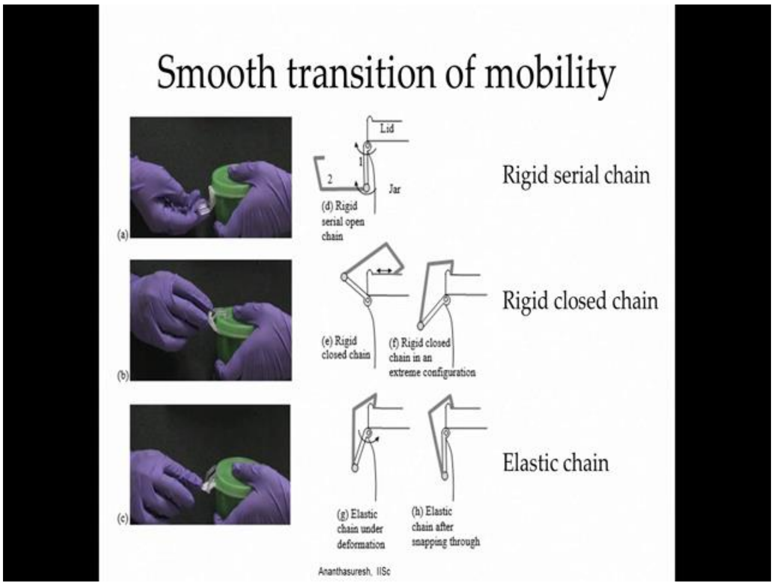

Let us look at this mobility that is attained, because of elastic deformation that is with complaint members as oppose to rigid members connected with joints. For which I have taken the day today object which is basically a can of a coffee powder here; there is a lid here for which there is sketch, but what I will show first is the real one that I got here. So, you can understand what this is, this is a can with a lid.

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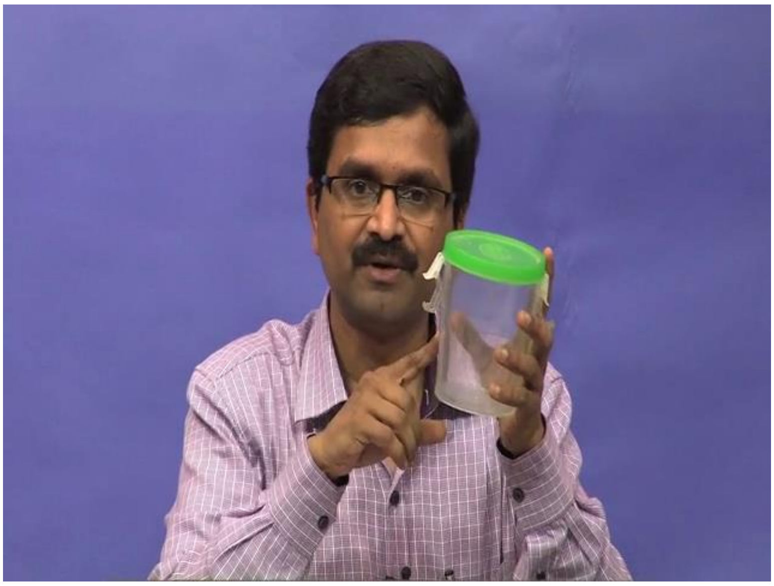

Here, is a can with a lid that can be screwed in and out, but if there is coffee powder in it you want it to be fresh. So, it has to be a tightly sealed one. So, they have this mechanism; if you look at this there is a hint here with the white one that is what I am going rotate and there is with respect to this white one this transparent one has another hint. So, what we have here is r r serial manipulator, but the movement I put it on the top of it like this I put it on top now it actually becomes slider crank; if I hold it like this where it is a top it is like a slider crack because there are two joints and a slider and a little slight rotation also here this slider crank and once this thing touches this lip of the lid then we cannot move anymore; it becomes a structure that is it cannot move anymore like a rigid body, but this particular thing can actually flex that is elastically deform. So, that it deforms and allows more rotations and when I push further it actually becomes bi-stable and actually snaps if I do it fast you can hear the sound as well. So, this is a mechanism that has smooth transition from a rigid body serial chain to compliant mechanism.

Let us now look at the sketches that we have in the slides. So, the first one shows that the there are two bodies like this; these two this is rigid serial chain what we call RR chain; revolute revolute chain, the moment it is placed on the top as I showed; when I move this back and forth this acts like a slider crack mechanism which is a rigid closed chain. The moment it touches here at this point it does not have any mobility, it just gets stack and it cannot move further, because this is abstracting it, but if you continued to turn this crank then this black thing has to elastically deform and then it can move and in that process it achieves kind of bi-stability by going and coming down to the perpendicular holding it very tight.

So, this becomes an elastic chain. So, we have rigid serial chain, rigid closed chain then and elastic chain and that is how this particular mechanisms works; in the same mechanisms you have three different things serial chain, closed chain both are rigid and then an elastic chain but a crucial to this mechanisms is this one which is the elastic segment.

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So, this is the animation we can just watch it. What I already showed with the real device. So, right now what you see is basically like a serial chain there are two rotations there. The movement you place on top of that that become a slider crank linkage and then once you bring it far enough and touches the lip on the can it becomes a structure cannot move, but you can still push it; at that point the transparent body will elastically deform and get this motion.

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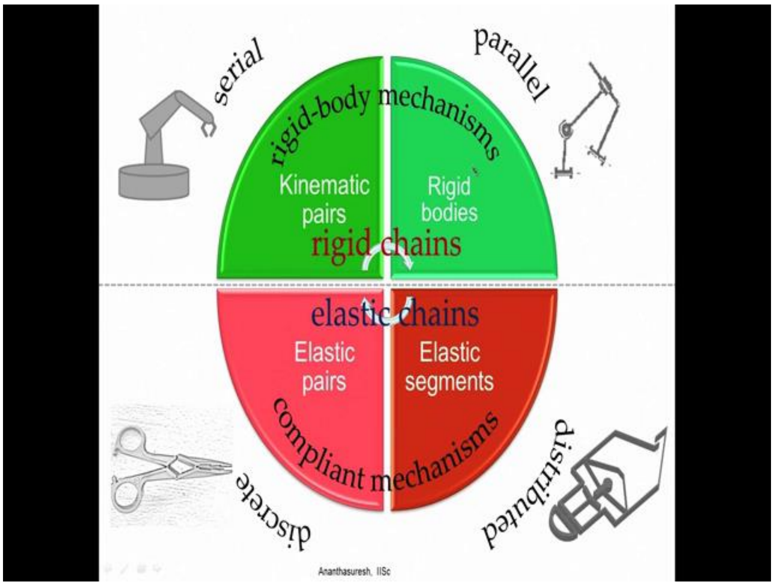

So, we can look at mechanisms in general as rigid chains or elastic chains; rigid chains will give us rigid body mechanisms and elastic chains will give us complaint mechanisms. These are the way we compare and contrast traditional mechanisms without elastic deformation and those that are complaint mechanisms that have an elastic deformation.

Here we have kinematic pairs which is the technical name for joints what we call kinematic joints that pairs, because they connect pairs of bodies and then those bodies are rigid bodies. So, every kinematic pair for example, if there is a revolute joint in robot manipulator these two rigid bodies are connected by a revolute joint and same thing here and so forth. Or we can also have parallel chains; parallel rigid chains such as this revolute spherical cylindrical and revolute; RSCR spatial linkage. It is a parallel mechanism, this is a serial mechanisms, but both are chains of rigid bodies where individual bodies in that chain are connected with various kinematic pairs as oppose that in compliant mechanisms a few two examples are shown here one of them is a forceps that I have a model here.

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In this forceps if you see of course, this is the blue one. So, here if you look at this it works like normal forceps; if you put something here you can pick it up or if you have sharp edges you can even use like a pair of scissors, but if you notice this does not have any assembled rigid bodies; there are of course, rigid segments, but it has flexible joints these four places which gives them gives this simple force the ability to work.

So, let us go back to the slide now to look at what we can call discrete compliance where there are these four flexible joints that give it the functionality that it has. As oppose to that we can call them elastic pairs this just like we have kinematic pairs we have elastic pairs here. As oppose to this we have other kind of complaint mechanism; we will see a movie of it later on this lecture which has distributed compliance; if this is discrete that is deformation is limited to a few locations here the deformation is for all the segments. That is what we call elastic segment; elastically deformable segments as oppose to rigid bodies. that is how we can characterize an understand complaint mechanisms as oppose to rigid body mechanisms; within compliant mechanisms we have those that have discrete compliance like these flexural joints like in this pair of scissors or a forceps or we can have the distributed compliance that is achieved with elastic segments which are basically beams here.

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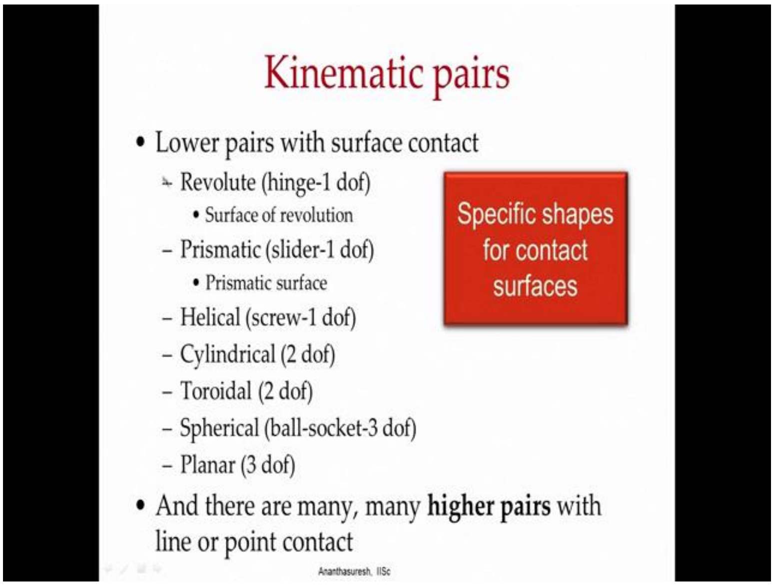

Now, kinematic pairs as we all understand from traditional mechanisms there are number of them revolute joint, prismatic joint, helical joint and so forth, and these are all lower pairs meaning here the contact between two bodies are going to besurfaces, but if you look at higher pairs that can have line or point contact, but what is true about all of these kinematic pairs is that they have specific shapes for this contact surfaces between the two bodies is that the joint connects. The kinematic pairs again it is called a pair because it connects two bodies and these two bodies should have complimentary shapes if you take revolute joint it should be surface of revolution of any kind; you draw any curve and have surface of revolution and you will get this revolute joint. Similarly if you have prismatic surface your prismatic joint or a slider joint; helical surface you get helical joint and so forth. planar surface you will get 3 degrees of freedom in a plane and basically if you put block on a flat plane that block relative to the flat plane will have 3 degree of freedom; the x motion, y motion both translations and rotation over the z axis.

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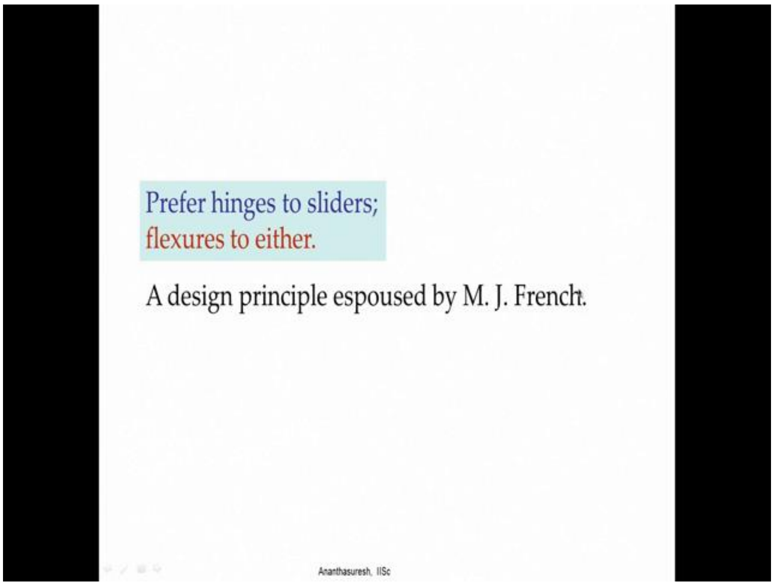

But then there are specific shapes for all of these things. Here is a design principle that one of the great designers Michael French wrote in his book; prefer hinges to sliders and flexures to either. What he means that whenever you can use flexural joints use them and you preference for those is above the Hinges and Sliders of course, between the hinges and sliders; hinges are better than sliders because hinges are revolute joints will have less friction than sliding joints. Prefer hinges to sliders; flexures to either. So, what Michael French; he is telling us here is that go for flexural joints whenever you can. So, here once again the discrete compliance if you want here is how you can get you can take a sheet and mill out a slot such as this.

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So, you can take a polypropylene sheet which by the way is a very good material for making compliant mechanism prototypes. You can take a sheet and it is just a planar or machining in millin; you to cut out these, what you get are the flexural joint that is the discrete compliance; compliance is here and here and here and here. If you put a screw here and turn the screw to at advance it this way when this moves up this going to move like this it may not be obvious when you look at this picture like this, but let us look at this like that; that is we have joints that which as indicated flexural joints; imagine then to be rigid body joints now or hinges.

Orange lines indicate abstraction of the bodies. So, here is one rigid segment, here is another rigid segment, here is a third one and fourth one of course, frame itself. This is discrete compliance; you just have few flexural joints and it does what you want. In fact, it terms it to be a Chebyshev straight line generating 4 bar linkage. Elastic pairs can be of many, many different shapes and here there is no specific shape like it is there for kinematic pairs.

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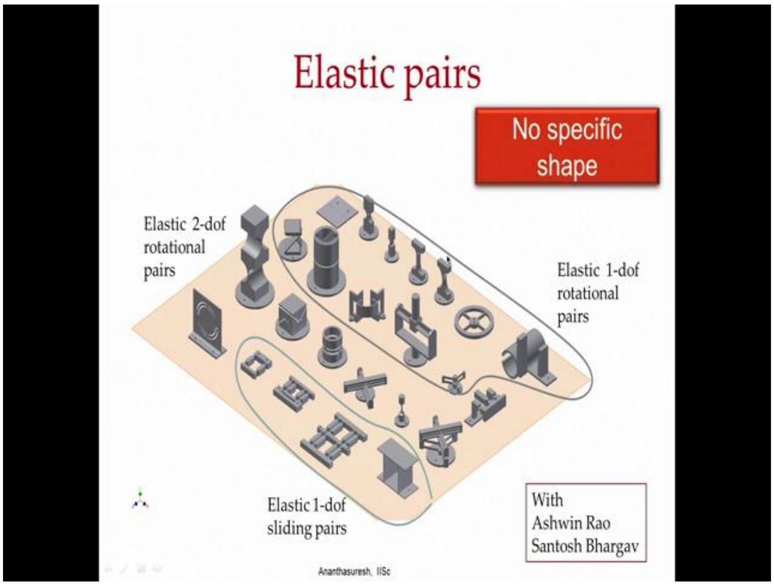

So, first single degree of freedom itself you can have number of sliding pairs; single degree of freedom revolute or rotational pairs single degree of so many things are there and 2 degree of freedom again a number of them are there. They are all different from one another in terms of their shapes, but they all do the same thing meaning 1, 2, 3, 4, 5, 6 all these six are going to give you 2 degree of freedom rotational pair and all of these encircled ones give you elastic 1 degree of freedom rotational pair and these are elastic 1 degree of freedom sliding pair. What you need to notice is that there is no specific shape for elastic pairs unlike it is there for kinematic pairs.

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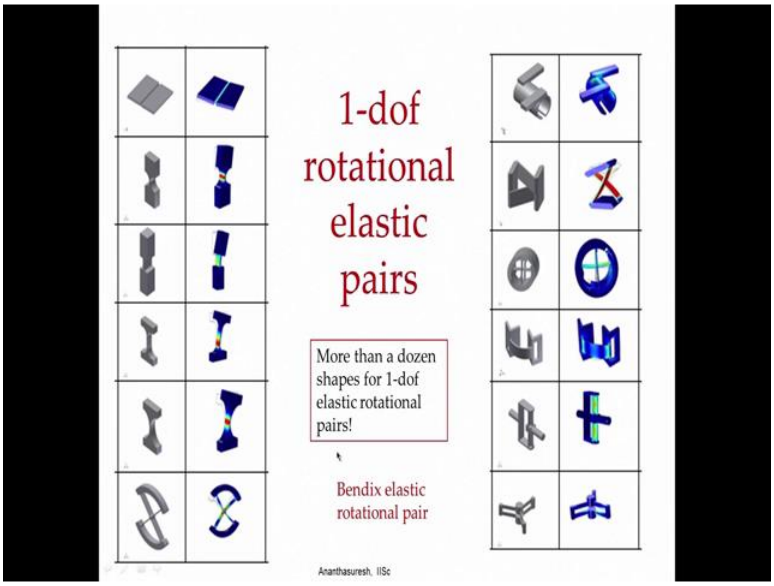

Here is the finite element simulation of some these joints that can be easily done and we will be looking at some are those little later in the course and all of these you can do and then say that they have similar behaviour as compared to rigid body joints or kinematic pairs. In fact, there is one called Bendix elastic rotational pair which has been in use commercially for a long time which is this one. If you types Bendix in google you will find that nice animation if you look at how will works it has been commercially every successful one and has lasted a long time.

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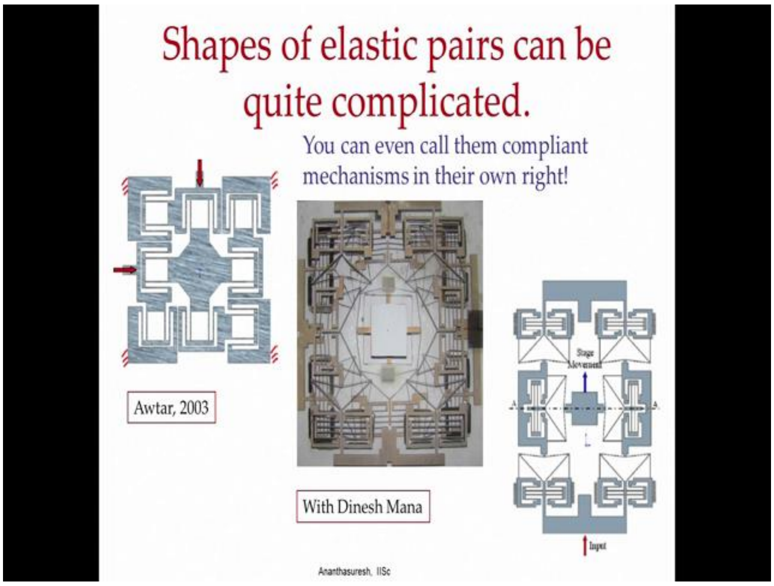

Some are these elastic pairs can be quite complicated as you see in the device that are shown here. These are basically 2 D translational sliding pairs like an x y stage, but all with one piece; this one if you apply actuation here the central platform will move purely in the x direction without any motion of y direction; likewise if you applied in y direction that will move purely here and not in the x direction.

So, it has that decoupled motion between x and y and rotational stiffness, other stiffness are very high. This particular one looks even more complicated that has two layers of actually metal here; that is a prototype that is a made which has displacement amplification included within this and have this two decoupled x y motions both translations and one layer of this shown here; take another layer turn it by 90 degrees and then attach at the central portion you get this mechanisms. Some of them can be very complicated because their shapes are not anything specific only the resultant motions you see this again emphasis the difference between kinematic pairs and then elastic pairs.

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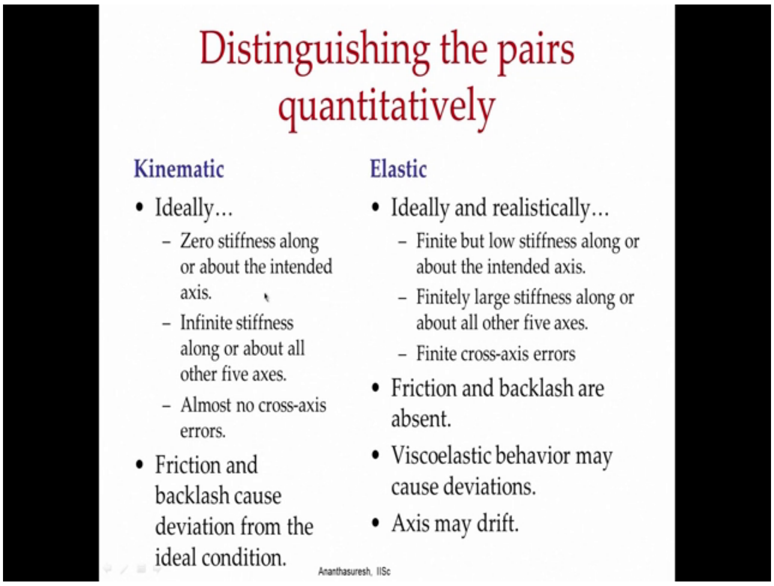

If you compare these two that is distinguishing kinematic pairs and elastic pairs; you have in kinematic pair ideally meaning that there is no friction or backlash, you have 0, stiffness along or about the intended axis. Let us say if it is rotation about x axis you have no stiffness or resistance to move it about x axis; to rotate about x axis or move along x axis and infinite stiffness about all other axis if you have one sliding joint like a piston and cylinder when you move piston and the cylinder there won't be any resistance or there will be little resistance are due to the friction are other things may be, but if there is no friction you will have no stiffness at all.

If you try to move to any other direction; you will feel infinite stiffness that is the characteristics of kinematic pairs and friction and backlash of course, will cause deviations from the ideal condition. As oppose to that elastic pairs they are more realistic they have finite, but low stiffness along or about the intended axis if there is a flexure about let us say z axis it will have stiffness, but low enough stiffness to rotate about the z axis and finitely large stiffness about other axis and there will also be this cross axis errors that is if you move about x axis there may be some movement about y and z axis also either translation or rotations.

So, there will be cross axis here the cross axis errors are usually very small or not present at all. Here we have friction and backlash whereas, a compliant mechanism there is no friction, there is no backlash. But viscoelastic behaviour whether it is made of polymers or metals can cause deviation sometimes they axis itself my drift a little bit which is not usually present or does not happen in kinematic pairs. We need to understand these two very well as to what kinematic pairs can do what elastic pairs can do.

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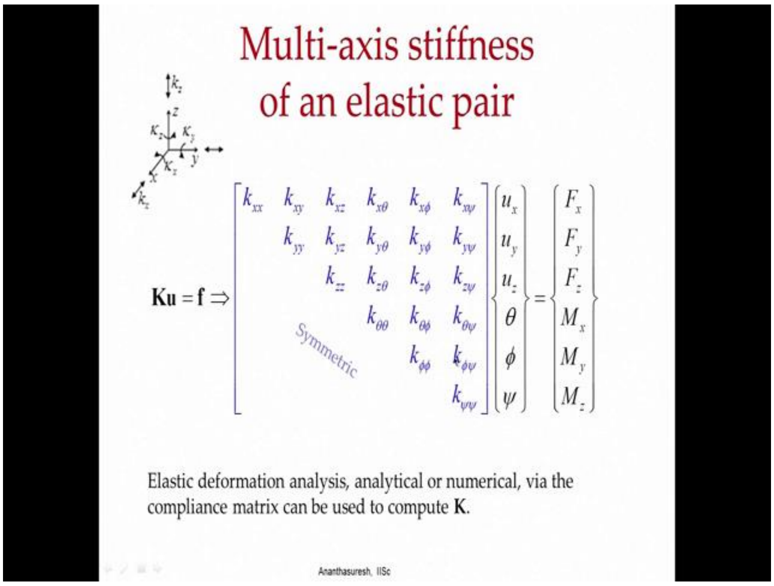

If you want to look at it mathematically for small displacements; we can put that in this form like Force displacement relationship where u's are displacements; let us say ux, uy uz; three translations and theta rotation about x axis, phi rotation about y axis, psi rotation about z axis and corresponding forces for translations and then movement for rotations. So, if you say Ku equal to f; K is the stiffness matrix which is multiplying the displacements which can be generalised meaning translation of rotations corresponding forces which again generalised forces and movements.

So, having this stiffness values kxx kxy and so forth you can characterise whether something is a kinematic pair and elastic pair. This is in the stiffness if it is let us say translational pair; sliding pairs about along x axis says then kxx will be 0 and all these other thing will be infinite because there is high stiffness are resistance about them likewise if it is a rotational one; k theta will be 0 all others will be infinite. That is how in the kinematic pair; where elastic pair if you take if I say rotation about x axis; k theta,

theta will be small, but not 0; finite, but small, others are not infinite, but they will be finite and very large and that is how one has to design elastic pairs.

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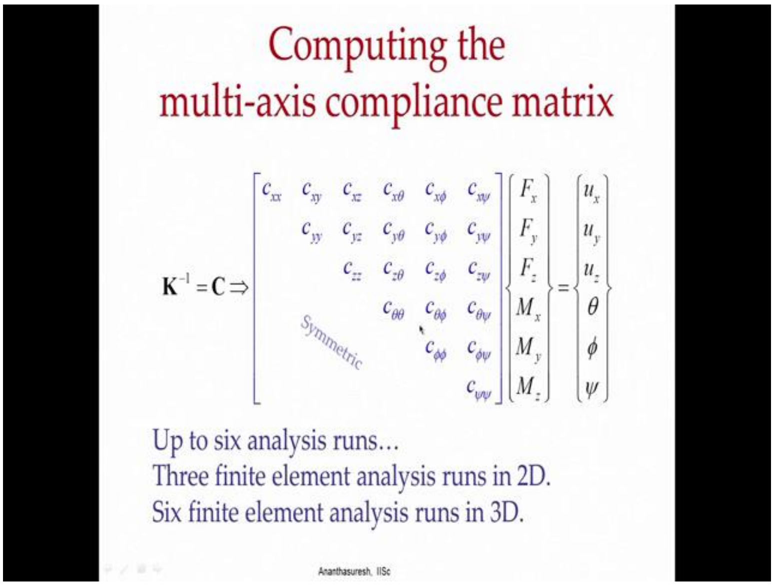

If you look at the reveres of it where I defined the inverse of the stiffness of the matrix as compliance matrix C; then we can talk about this. Let us say if I want translation about the z axis; then czz that is compliance it has to be very high all others have to be 0 because of the compliance opposite of stiffness. Again we can talk about how to design elastic pairs by looking at these values; there will be some target value depending on how much stiffness you want about the intended axis which should be low stiffness or high compliance and about other axis high stiffness and low compliance slowly you can look at those thing and design.

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Now, having look at that; if you look at this mechanism this is distributed compliant mechanism; there are no elastic pairs here even if you want to look for them you do not find; you only find beams that are long and there are some holes here and there and how does it work? Again before I show the mechanism let us look the fact that that there are no elastic pairs in this. That is a characteristic of distributed compliance mechanism and this deformation it moves as you will see is uniformly distributed throughout the mechanisms more or less do not be the same everywhere, but entire mechanisms is going to be deforming and you have large displacement here, but small strain of course, when I show the device you can see that there is a small strains and less you do finite (Refer Time: 22:30) analysis or some other analysis, but you can see that the deformation is there, but it is causing large rotations and displacements rather than stressing or straining individual parts and such mechanisms are stronger than those with elastic pairs because the forceps I showed; if I applied too much load at the flexural joint it can easily break whereas, when you take distributed compliance mechanism it will not but of course, there is enhance scope for design because if we take elastic pairs you can just imitate the rigid body mechanism replace a joint with a flexural joint that is a kinematic pair with an elastic pair, but the movement you go for this concept of distributed compliance then you can design them in many different ways.

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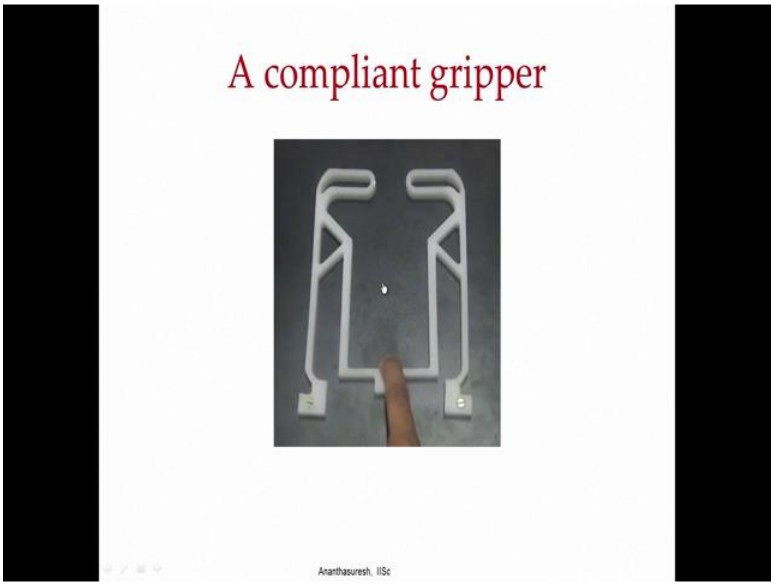

So, here is the device that is fixed over here and over here you can see little screws this is actually a board and when I apply force here; it will going to move like that. Looking at this you can say that I am actually straining a particular portion a lot this is gripper. So, when you apply force some where two things are coming to grasp something and grip something

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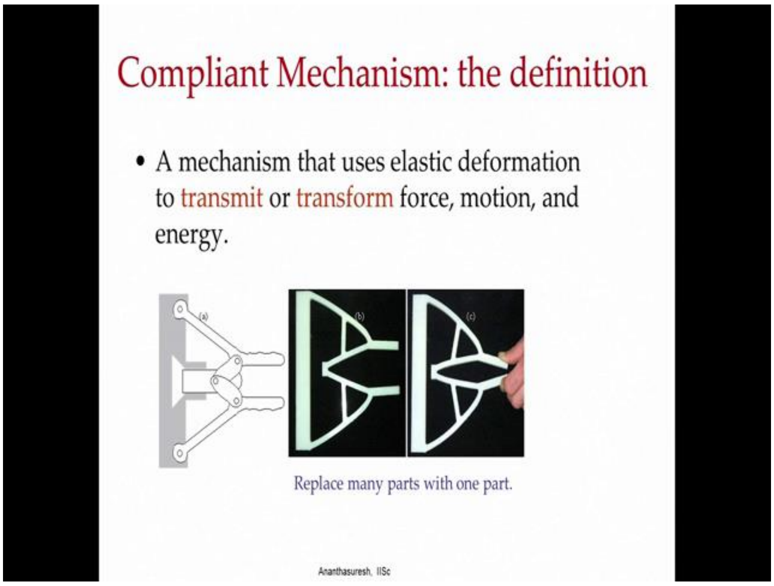

After all these; if you want a definition for compliant mechanisms; here it is. A complaint mechanism is one that uses elastic deformation to transmit or you can put also and if you want transform force, motion and energy. So, if you have a rigid body linkage here which has these joints when I press these handles; it will move like this and close the gap; it is a mechanisms because if you put an object there it will do some work on it; the same thing you can get with a thing that does not have any joints only you have elastic segments here this transforms your force that you applied at the handles to somewhere else to do some work force, motion or even energy; the transform part of it will come to little later in this lecture.

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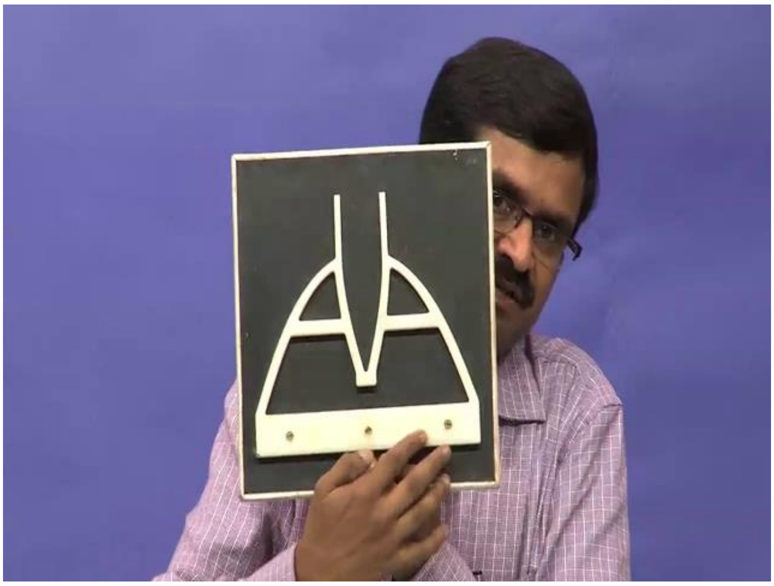

So, I have this device here to show you where you have this thing there it are fixed at the bottom portion and if I press these handles it will move down. In fact, if you were to have this device in your hand if you put your finger over there and do it we can actually make yourself scream meaning that it has very good mechanical advantage; with little force you can generate lot of force at this point, so this way mechanism that amplifies force. There are other things where you can amplify displacement if you want. So, here is one that amplifies displacement; let us look at the screen first.

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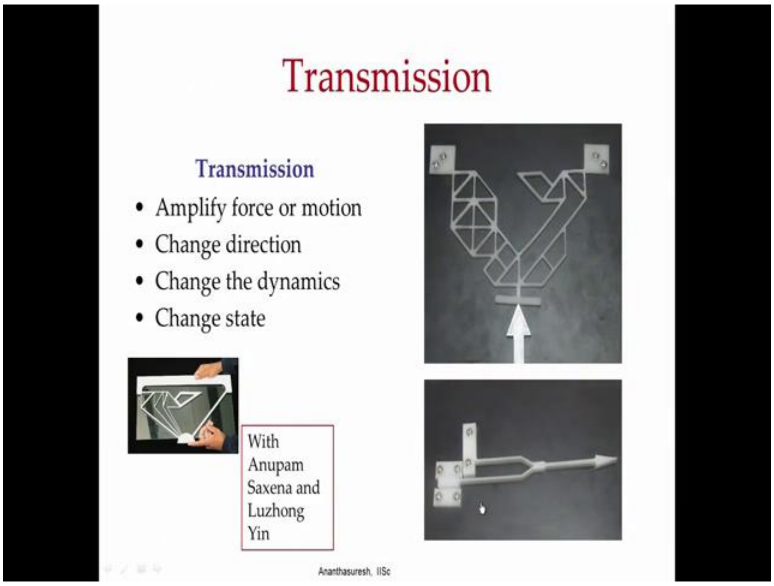

So, there are these movies of real prototypes where you are applying a force you just a big aluminium arrow that you have made to illustrate. So, apply a force here; it is moving large with the displacement over there. This is a displacement amplifying mechanism; complaint mechanism; it amplifies complaint mechanism amplify forces or motions and they can change direction and change the dynamics also change state in some sense. If it is a bi-stable device it can have two stable states can do that.

Let us look at a changing direction mechanism which is at the bottom here; when we apply force over here to the right this goes like that. I have a real device that shows here.

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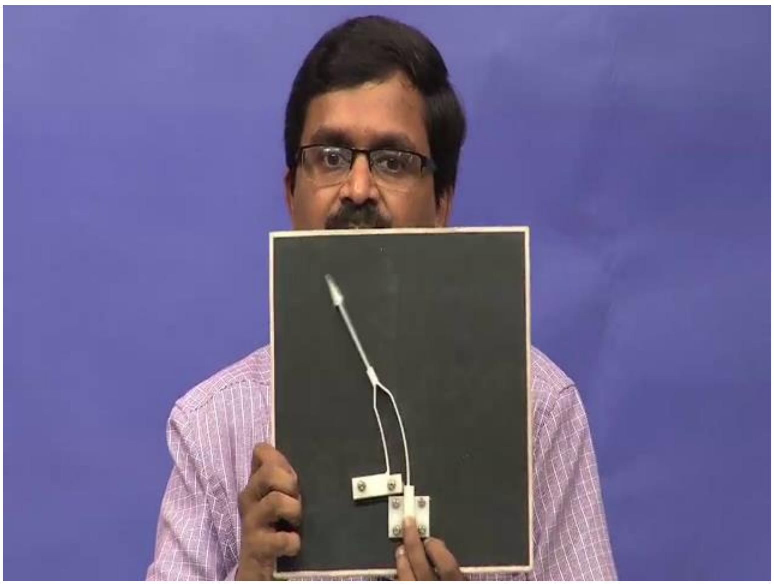

So, if I apply force; I am pushing this up and down. So, have to (Refer Time: 26:26); if I pushing it up and down like this it goes like that. It can change direction I am vertically pushing up and down that can goes you can see how much deformation that it has and how much output it is giving and here is another device.

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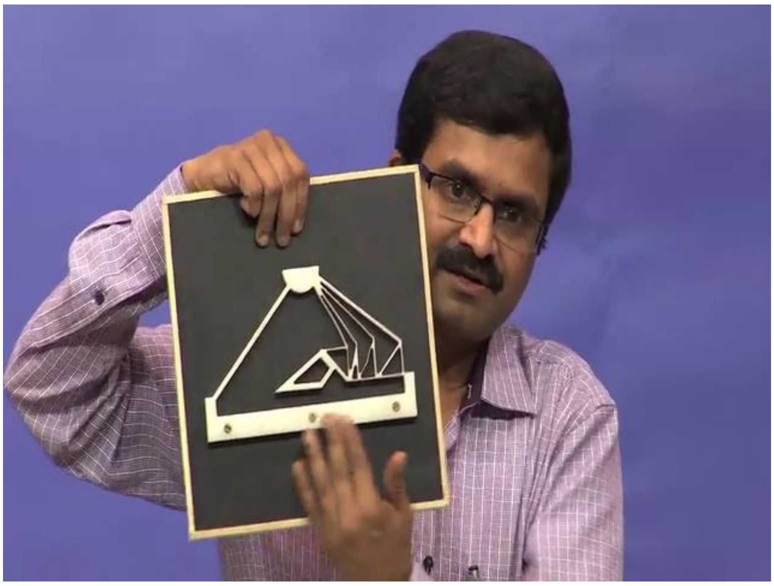

This is also a displacement amplifying complaint mechanism which is fixed over here this entire piece is fixed that is screwed on to this board; when apply force downwards this thing moves upwards by a large amount right this displacement of (Refer Time:

27:03) complaint mechanism and when you hold it in your hand you would feel that there is large displacement and large rotation, but there is very little strain and if you will if you do billion times this device not likely to fail.

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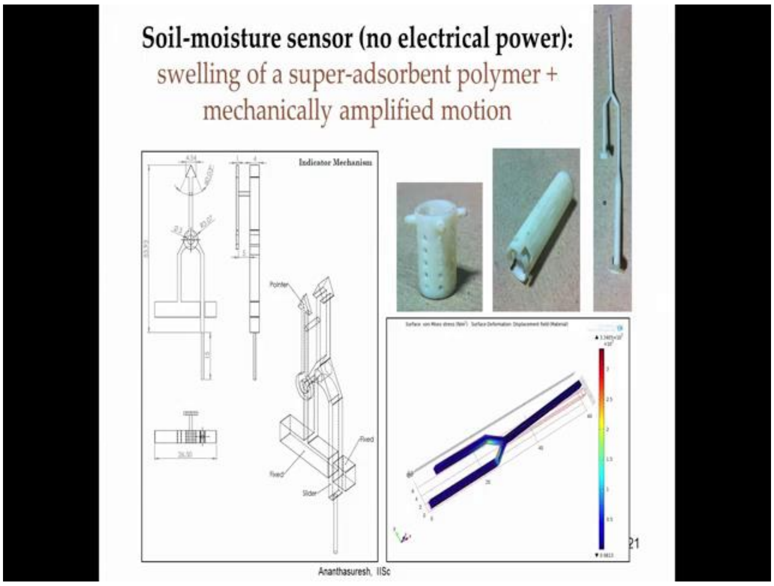

So, complaints mechanisms can act like transmission because transmit force, motion as well as energy. So, if you look at that device that I just showed changing direction one; it will put to use and here one of my students have created a Soil-Moisture Sensor without using an electrical power. It works by using a material super-absorbent polymer which swells and basically expands by about 300 percent. Now if you put a complaint mechanism over that and do not let it expand as much as it wants to; it will apply force and move this mechanism as I just showed.

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So, based on that (Refer Time: 28:09) something called Neer Samiksh. It just as call mechanical; you should put little bit of moist sand in here in a cot ridge and this there is a material super-absorbent material which observes moisture from the soil just like roots of a plant would do and then based on the this pointer that is over here would move and indicate 1, 2, 3, 4, 5 levels based on that even somebody who does not read there is type of soil and type of crop you put in based on 1, 2, 3 it will instruct them as to how much water they have to put as you can see in the label closed up here.

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And all that is done with a simple complaint mechanisms as this video that is spared up for showing it is about it takes 30 minutes for this to do and you can see that pointer moving. Let me play it again. So, you can focus on the pointer which is here now and it is moving as there is moisture absorbed and it is (Refer Time: 29:11) expand complaint mechanism takes that force; you see a large mechanism takes the little force generated by an expanding polymer that can move this; that means, that you can have little force and generate a lot of motion. Let us look at the transmission part; transmission part is you already look that.

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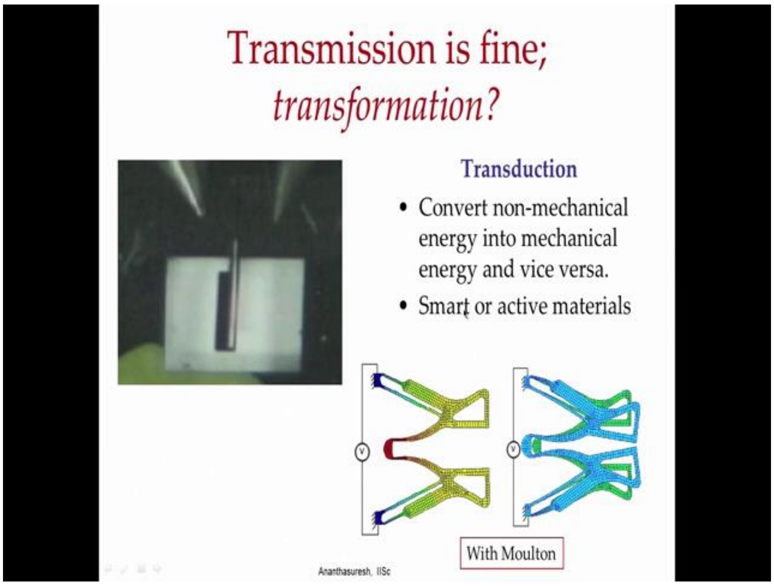

Now, let us see what transformation it can do or transduction. Transduction as many of you would know is converting one form of energy into another form that is exactly what this does. Here we have two electrodes when apply electric potential between them as we will see what happens. So, it is getting hot it is also moving. It is electro thermal actuator which if I put it in slightly different form I get a gripper with embedded actuation.

So, here an elastic material which is also electrically conducting, thermally conducting and if you apply potentially between two points you say able to generate motion and it generate to the to the mechanical work as well you can move just like the device that I showed a few slides ago. Here you are actually transforming electrical energy into thermal energy and then mechanical energy that is what complaint mechanisms can do.

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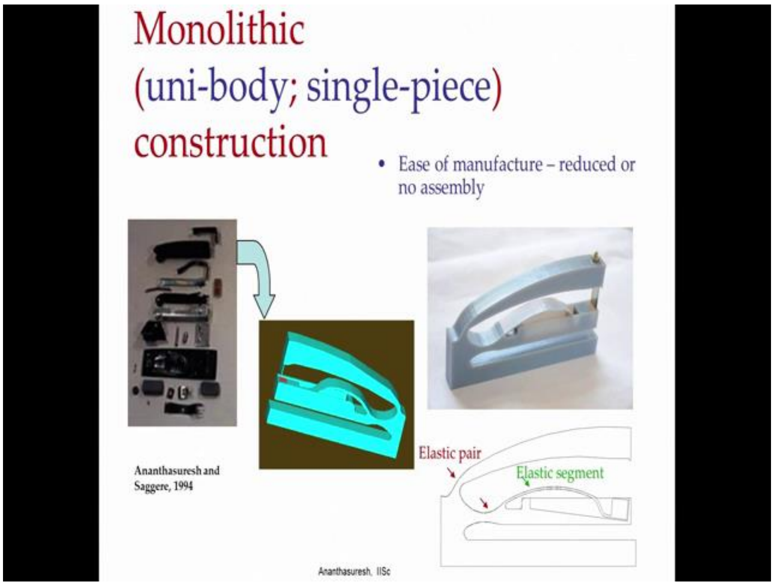

And there are lot of advantages of complaint mechanisms; if you take a normal stapler what you see here is a stapler that has only one piece design. So, entire thing can injunction moulded as one piece except these metallic insert also can be put as insert in injunction moulding; this is as oppose to normal stapler if you break it apart there will be many, many parts in 1994 when (Refer Time: 31:06) there were actually 20 parts there, but you can make something that is like unique body as single piece complaint mechanism.

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And here is one another version of that are this is a windshield wiper mechanism that was done by Sridhar Kota who is professor of University of Michigan where you can have day to day things made of complaint design so that you can get one piece design there is a company called FlexSys, there you can learn more about this and many more designs.

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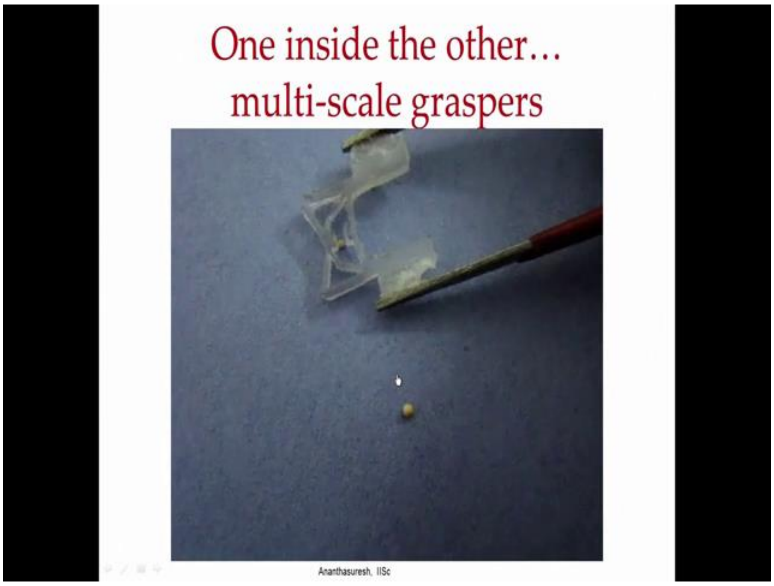

And there are many other things that you can do one of them is the miniaturisation as it will show here towards miniaturisation you have normal forceps to which a complaint mechanism is attached; when you close the forceps you can pick up something. So, the idea is that if you want to here is an (Refer Slide Time: 32:02) ball if you want to pick up something small you do not have to make necessarily make things very, very small.

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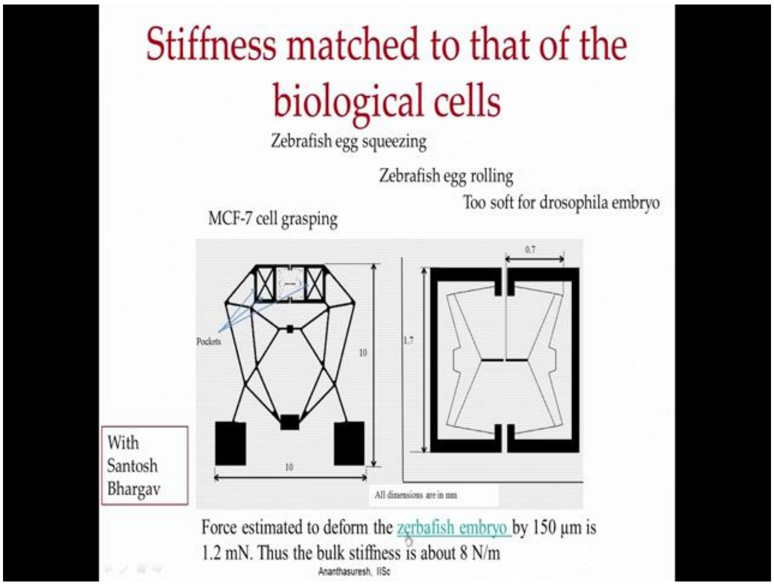

And here is idea of that; if you want to make a complaint mechanism that can pick up single biological cell; biological cells are of the order of the animal cells rather of the few microns that blood cell one of the smallest animal cells is about 5 microns 7 microns in diameter and all other cells slightly bigger than that, but the order of microns if you want to pick that up you take bigger complaint mechanism put it in that little complaint mechanism small one whose magnified views shown here and here is where the cell would be grasped and some other beams here will be very small they can be as much as 5 microns in width and a couple of few microns along the thickness direction with which you can hold zebrafish embryo single biological cells and so forth here.

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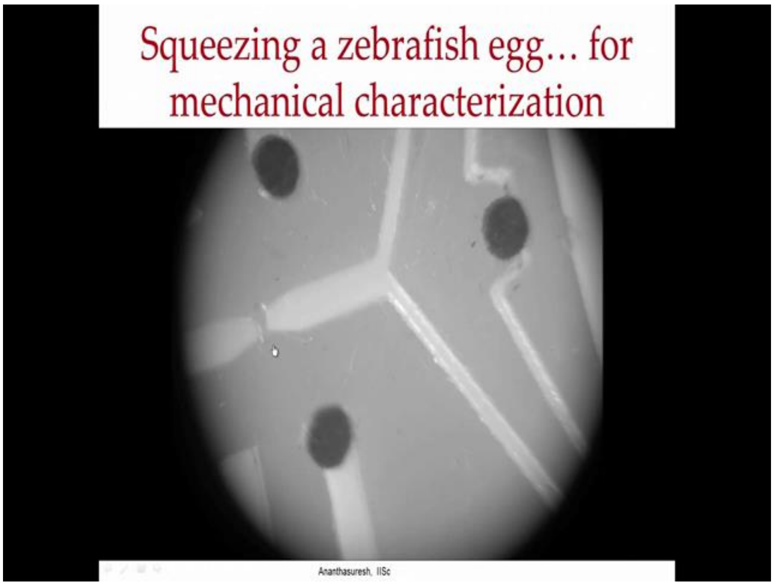

Whereas zebrafish embryo you will see that two the gap I showed in the previous slide and you can actually press; a cell is like a dropt if you will you can actually grasp and press on it and you can do mechanical characterisation.

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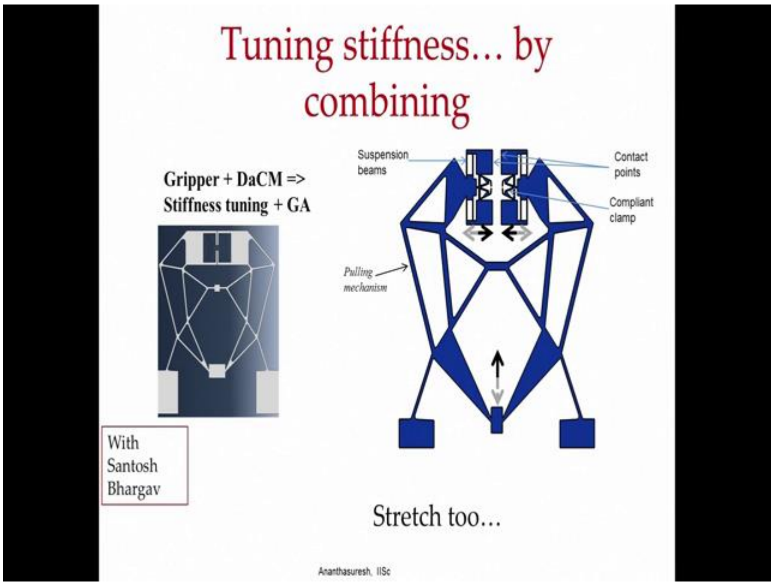

And there are many other things at that you can do by having this complaint mechanisms that can give you geometric amplification G A or you can tune their stiffness the way you want, you can go down to the stiffness of single biological cells which have very,

very low stiffness as well as very high stiffness of many other things as well. We will pass here and continue in the next lecture.