Compliant Mechanisms: Principles and Design
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Lecture - 67
Micromachined accelerometers with Displacement-amplifying Compliant Mechanisms (DaCMs)

Hello. We are into the third case study which is using compliant mechanisms to measure forces. So, all you need for that is a way of measuring displacement that you can do in many ways especially at the micron scale, where the forces are small in this case we are talking about Micro-Newton force sensor made using compliant mechanisms.

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So, this work has led to what we call a microN it is a Micro-Newton force sensor you can also go down to smaller forces than that it looks like this. Compliant mechanism is hidden inside little one and that is a crucial element here. This was developed by Santhosh Barghav which is part of his PhD thesis who has now accompanied. And a number of students in particular Ashveen Maheshwari and Harshala Gugale and Gautham Baichapur did a lot in calibrating it and few other students also contributed to this work.

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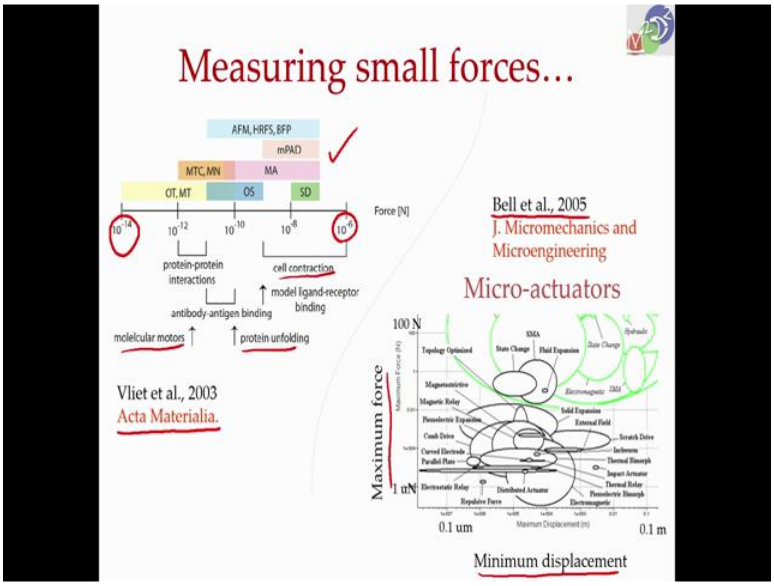

So, when you think of measuring small forces there are lot of techniques now. In fact, the smaller the forces the more the techniques are. So, starting from Micro-Newton these are all Newton this is 10 to the power minus 6 Newtons all the way to 10 power minus 14 Newtons like 10 femtonewtons. There are number of techniques these are all acronyms, if you look at this paper that is sighted here you would know what these are. These MA is micro aspiration, AFM is atomic force microscope, OS is optical stretching and so forth.

These are the twisting cytometry magnetic twisting cytometry that crick had pioneered all of these. And look at cell contraction, protein folding, molecular motors all of those biological things have very small forces. There are number of techniques for doing this. If you look at the micro actuators, this is measuring forces we are talking about actuators. We have plotted now maximum force and minimum displacement that actuators capable of doing. Again there are lot of different actuators. This is a paperboy Mike Ashby's Group, 10 years ago or more than that. So, they have lot of actuators they have put here. So, we have actuators, we have force sensors.

So, is that enough for us to work with biological cells where the things are very small; but it turns out that there is plenty of room in between. So, you look at either forces or displacement whatever that is available out there for you to take.

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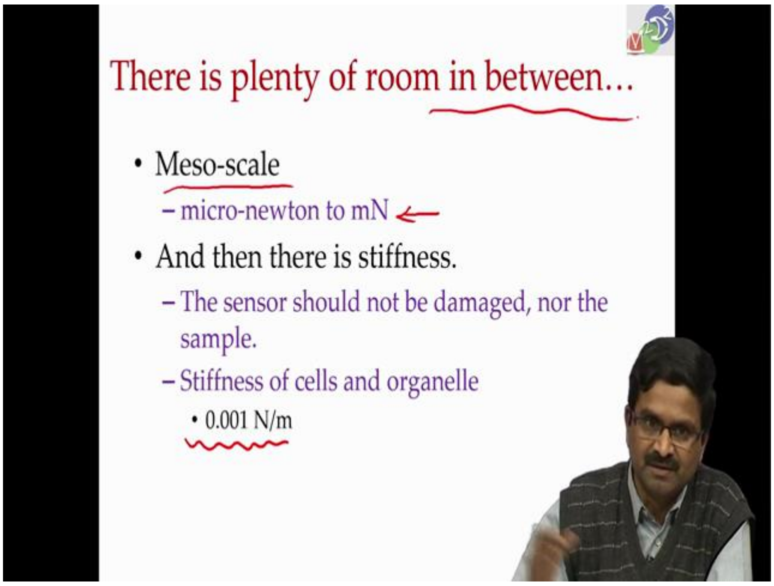

But there is a gap at the meso-scale that is Micro-Newton to milli Newton range, if you call that as a meso-scale. It is hard to find useful sensors commercial available. And then we also have the problem with stiffness; some other sensors even though they are able to measure they could damage the specimen. As we already discussed in the last case study that cell stiffness can be as small as 1 milli Newton per meter.

So, such a small stiffness unless your sensor also matches that it will be a problem to handle biological cells. So, there is plenty of room in between the micro and the macro size.

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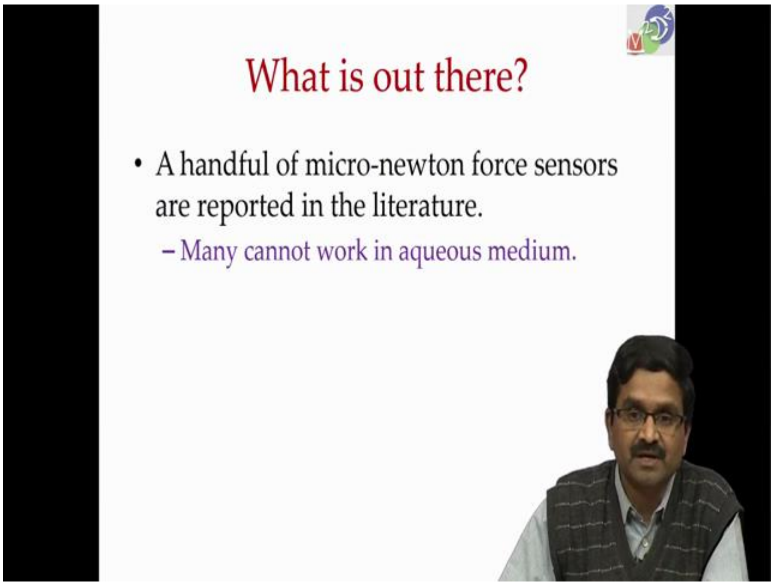

So, in terms of what is there many of these sensors cannot work in aqueous medium.

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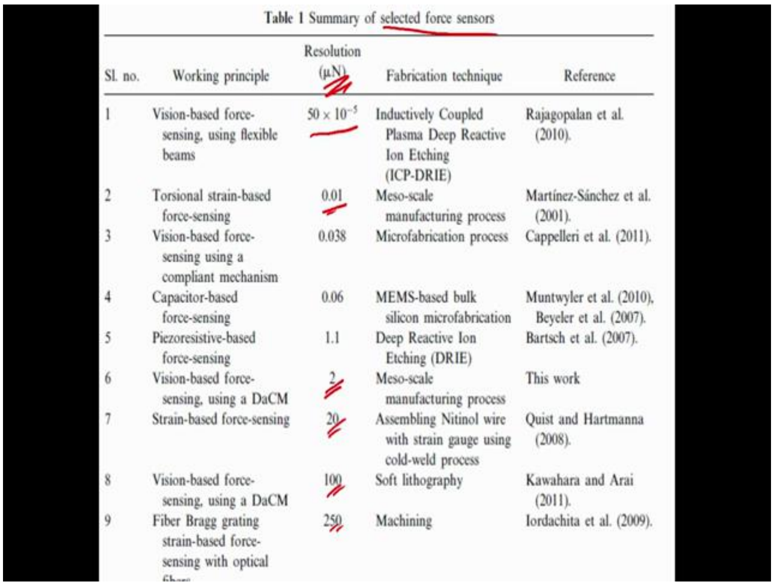

Table 1 Summary of selected force sensors

Sl. no.	Working principle	Resolution (μN)	Fabrication technique	Reference
1	Vision-based force-sensing, using flexible beams	50×10^{-5}	Inductively Coupled Plasma Deep Reactive Ion Etching (ICP-DRIE)	Rajagopalan et al. (2010).
2	Torsional strain-based force-sensing	0.01	Meso-scale manufacturing process	Martínez-Sánchez et al. (2001).
3	Vision-based force-sensing using a compliant mechanism	0.038	Microfabrication process	Cappelleri et al. (2011).
4	Capacitor-based force-sensing	0.06	MEMS-based bulk silicon microfabrication	Muntwyler et al. (2010), Beyeler et al. (2007).
5	Piezoresistive-based force-sensing	1.1	Deep Reactive Ion Etching (DRIE)	Bartsch et al. (2007).
6	Vision-based force-sensing, using a DaCM	2	Meso-scale manufacturing process	This work
7	Strain-based force-sensing	20	Assembling Nitinol wire with strain gauge using cold-weld process	Quist and Hartmanna (2008).
8	Vision-based force-sensing, using a DaCM	100	Soft lithography	Kawahara and Arai (2011).
9	Fiber Bragg grating strain-based force-sensing with optical	250	Machining	Iordachita et al. (2009).

There are a few, but they do not work in as in aqua aqueous medium that is the water medium in which cells are happy and alive. So, some of them are listed here, some of the selected force sensors from the literature. The resolution we talked about in the context of case study one with accelerometers. Similarly, what is the smallest change in force that you can detect? Here is one that detects about 50 or I would say 5 Micro-Newtons, 10 power 5 Newtons or 5 Micro-Newtons. There are some which can measure 0.01 Micro-Newtons also.

These actually Micro-Newtons is much smaller this is 50 into 10 to the power minus 5 Micro-Newtons very very small in this particular case what they have made vision based sensing. There are others in terms Micro-Newtons some are 2, this is our own work some are 20, 100, 250 and so forth. There is varying capability so many of them are kind of research based force sensors they are not commercially available.

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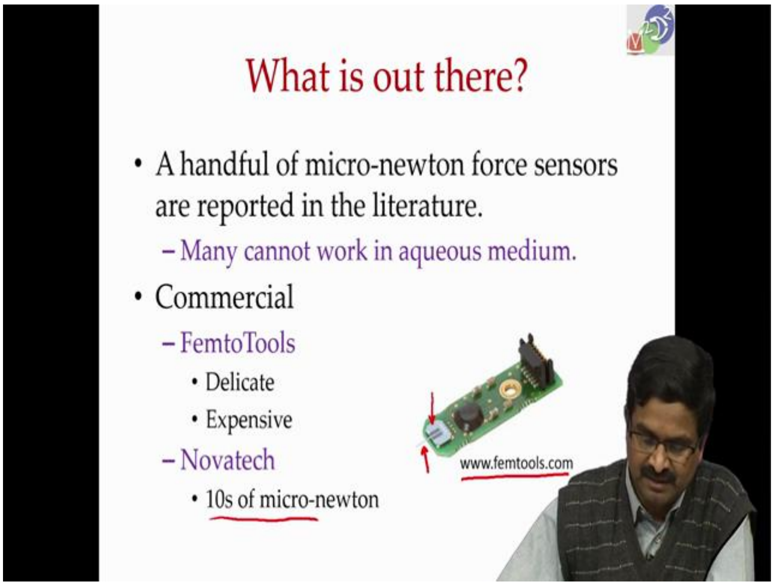

Commercial available ones there are a few this is from femto tools. There is a very tiny probe here and these all MEMS chip, measures, capacitance change when there is force and there is displacement of the probe that changes the capacitance and then there is electronics we have to put this. It also works in water, but you have to put an inclined angle and it is very very delicate; you could just break and lose hundreds of Euros on this. So, there are some that can measure. There are others that are capable of measuring tens of Micro-Newton, there are very few in the commercial world also.

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So, with the Micro-Newton force sensors that I wanted to work we had set some goals for ourselves. One is that it should be inexpensive it should not be that that probe anyways it is going to be delicate if it has stiffness that matches to another cell, but when it breaks we should not be losing a lot of money so we wanted to make it very inexpensive. And the idea was to use mechanical amplifier which is our compliant mechanism. It is vision based, because we do not want to use any other sensitive technique or transduction technique. Because anything else you bring in whether it is electrical, magnetic, thermal all of them are going to interfere with the thing.

And one confidence that we have is that we can design the stiffness the way we want. So, whatever range we want. And excepting a digital microscope to measure the displacement on the output or amplified displacement all others are simple enough parts to be made in a normal workshop it should also be easily usable. These are the things that we set out as requirements from the end user viewpoint.

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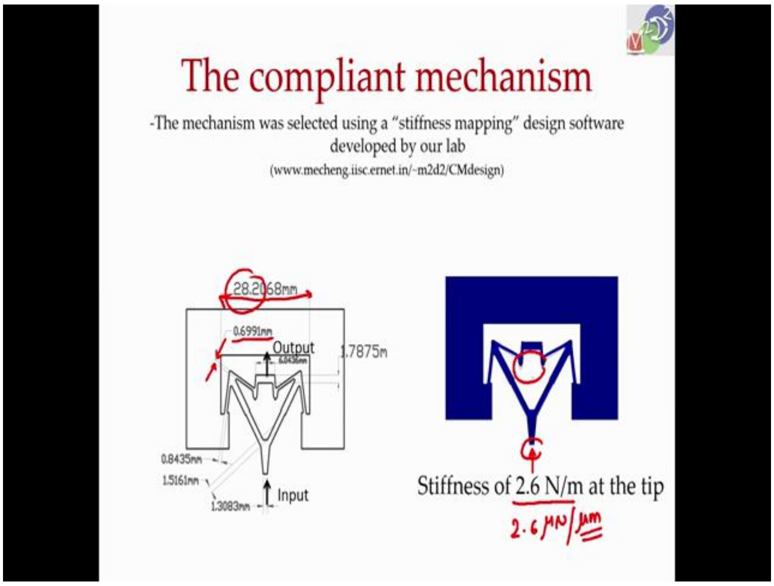

So, our compliant mechanism as you see is quite simple. So, all we have is one DACM you can see. The displacement over here is small, it is larger over here. It has a stiffness of 2.6 Newton per meter at this step. That is if you apply 2.6 Newtons you will get a meter displacement; that is a lot this is of course this will break by that time. So, instead what you can do is 2.6 Micro-Newtons and that would lead to 1 micron display. That is what we want; so Micro-Newton force micron displacement. So, stiffness has to be of that range micrometer displacement is amenable for measuring using visual techniques, just optical microscopy you do not need to go beyond that. So, we can go for enough of this shelf digital microscope and measure this very small displacement. So, that was the principle.

Look at the size of it, it is 28 millimeters. So, this length from here to here is 28 millimeters and it is not that small in fact does not need to be. So, even this width here if you see the narrowest beam which is over here that one is 0.7 millimeters, so seven 100 microns. You do not need to go for micro fabrications also to make this; I will tell you how we had done. So, we can design these things, to have the stiffness that we want so that small forces applied over here will cause measurable displacements using a digital microscope.

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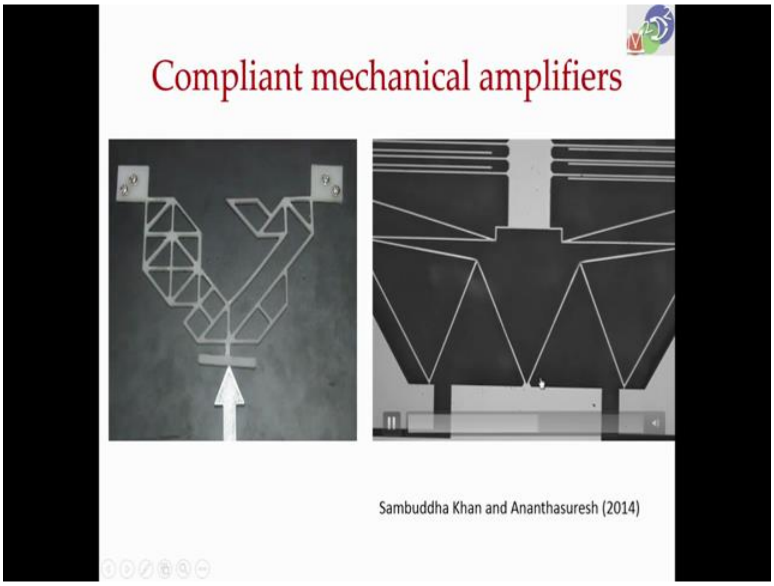

So, here are some of the things that we have already seen when you apply force here how it goes. We had also seen accelerometer where the DACM is there. So, there are enough of these at our disposal.

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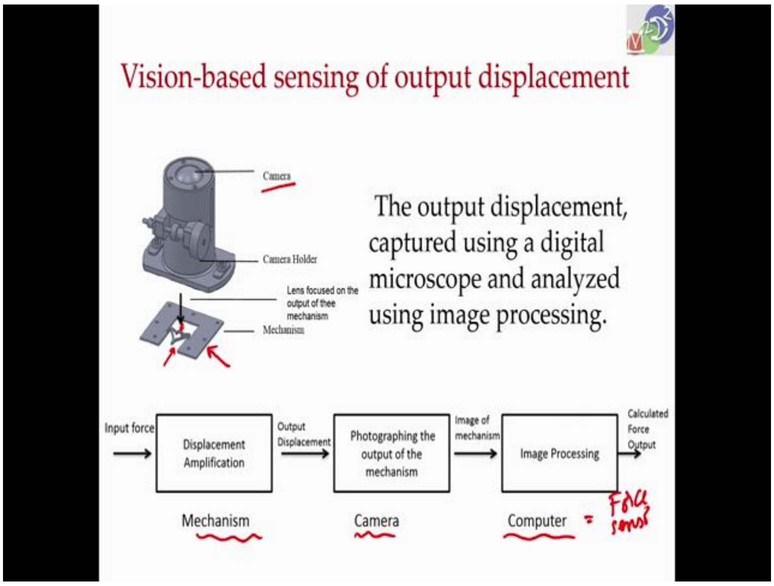

And we also wanted to make it easy to you. So, the delicate element is this even if it breaks. We take care to make it strong enough, but can still break if the handling is not right. Because, suppose to move in the plane if somebody ranks it out of the plane it is going to break so we want to make it more like a cartridge here. So, this cotted like thing can be slid into this digital microscope this is the microscope some camera; that is that is there you can put a USB connection to your laptop so that will measure the output displacement.

So, if it breaks we can put another one so that was done. Basically a camera plus a compliant mechanism and some computing lead to a force sensor. This can be done in number of ways.

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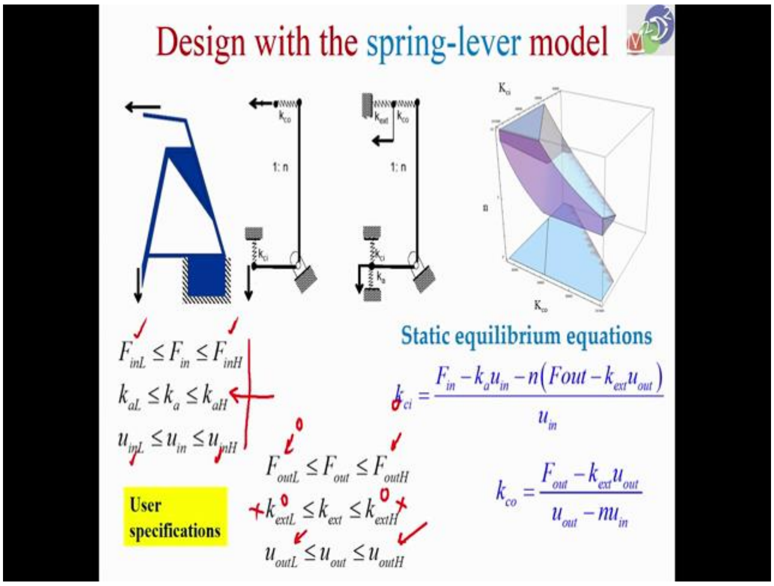

And of course the image processing where that computing will be there. So, to design this we had used this spring lever model and put in our requirements as upper and lower bounds on the input force; that is what we want to measure. So, we know what to put here. And what is the actuator stiffness; so that is in this particular case you are going to move that is not so much and that is does not matter here. How much displacement of the input we do not care, but we have to care in terms of the objects stiffness here, because the input for this comes from the cell.

So, over here what we mean is actually stiffness of the cell. If we know that for this force how much displace we can expect we can put that in, because we have approximate idea of what the cell stiffness is. Or the output there is no force in this case, so the force is 0. So, we put 0 0 on both sides, you do not leave moose. And external stiffness, so this also will not be there 0 0, but we are interested in output displacement. So, we can say we are happy from 1 micron to let say 3 microns or something like that we can specify this. And then generate the feasible space for it, the three dimensions in k ci, k co and n that is spring lever model parameters.

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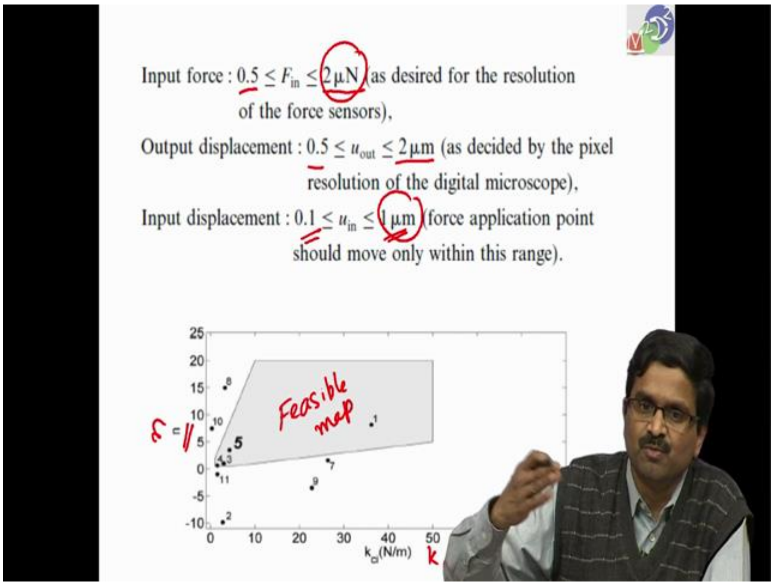

And then look at various compliant mechanisms that are there. Input in this case we put the input force 0.5 to 2 Micro-Newtons that is what we expect the cell to experience, output displacement half a micron to 2 microns is what we want. Minimum half a micron should be there that with some image processing techniques you can figure out in optical microscopy itself. Input displacement, we put 0.1 to 1 micron that is in view of the input force. If I put 2 Micro-Newtons and 1 micrometer as the input displacement I mention that the stiffness of the cell where we are getting this force from when we are squeezing the cell or cell exhorting force we wanted to be in the range of 1 Newton per meter or a 1 Micro-Newton per micrometer.

So, you can see at some of them were lying inside, some of them were outside, this is the feasible map. And you can see that in this particular case you are plotting N versus k ci, not k co because that does not make sense there is no output force there is no output spring here; you just need to move it is more like a indicator mechanism.

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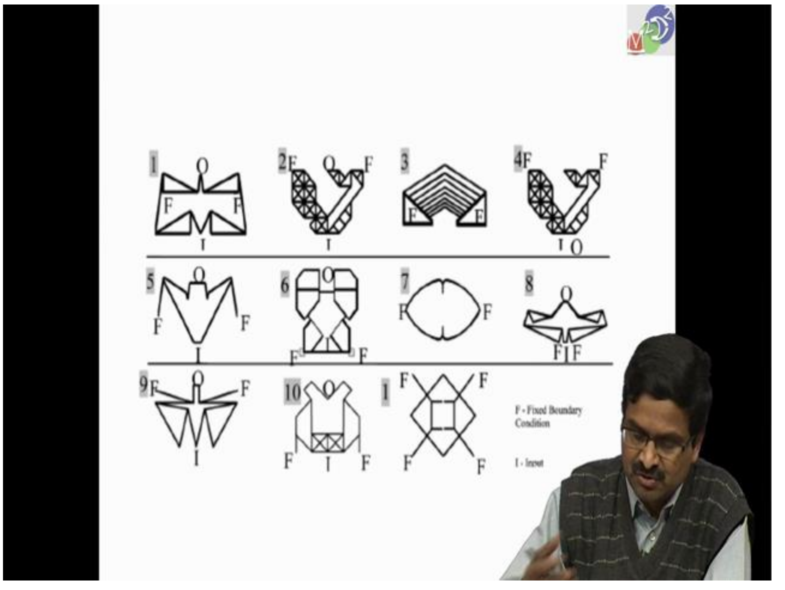

So, a number of mechanisms were considered.

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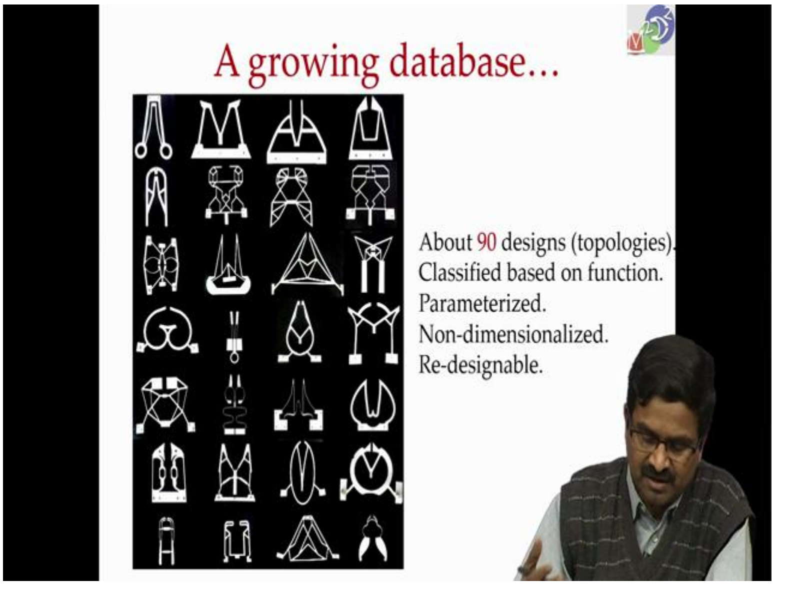

And using this technique we are able to choose one. So, like this is a growing database we have lots and lots of these grippers in our database.

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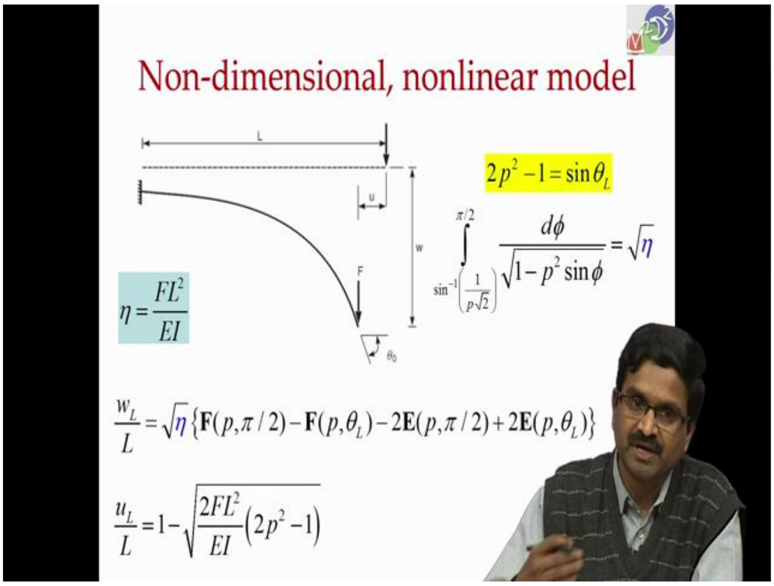

So, we also use this non-dimensional analysis to see how we can resize them as we need. We have discussed this at length in this course in the earlier lectures.

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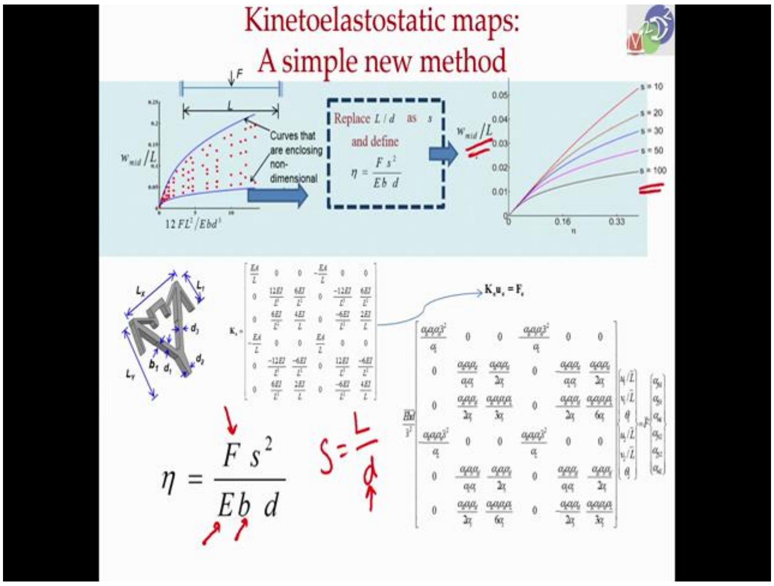

And how we drew for different slenderness ratios and decide the size of it, which also we went over in the last lecture so to see what either the overall length this S slenderness ratio is L by d if d and b are fixed by the manufacturing technique E is fixed by the material that you have chosen, and of course F is the minimum force you want to measure based on this map S value and our eta we can see what displacement we know how much output displacement we want; we actually decide this size how much large we need to make.

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So, just to see that compliant mechanisms before we go to this Micro-Newton force sensor you can see a mechanism such as this we had seen a real device when I apply force here up and this thing here moves like a pointer. So, in olden days people used to use things like that to measure pressure and so forth.

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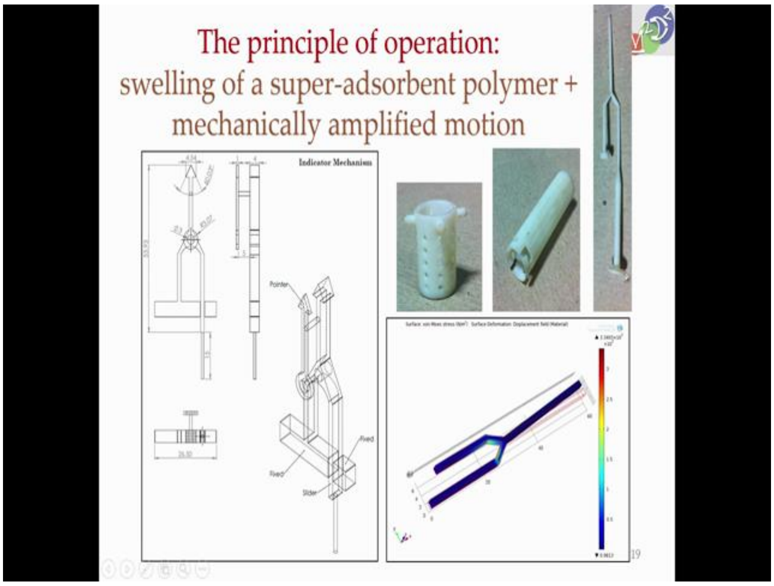

Here we use this to measure soil moisture level. In all mechanical thing there is a little canister where you can put moist soil, and there is a wick like thing and it is filled with super absorbent polymer which absorb the moisture from the surrounding soil and it swells. The swelling is what is going to push here the same mechanism we saw and it moves this pointer.

So, the mechanism is shown here now the solid model indicator mechanism. And just moisture swelling this is a very little force it expands by a factor of 3 that is 300 percent, but it is force will be very limited. If you put your finger after filling this super absorbent polymer there it would not even move much, because your force is enormous. But, we have to design a compliant mechanism which has stiffness low enough that an absorbent polymer can push this and move this pointer as you will see.

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So, this was embodiment design and it was all done. And here is where the pointer is going to move. The pointer is over here now and when there is more moisture or less moisture it would move.

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So, this video shows you watch this pointer here; of course this takes about 30 minutes. So, it is a speeded up movie. So, you can see this pointer actually moving from there to here there is moist soil kept in this super absorbent polymer thing. So, it actually moves all the way down. So, it is possible to do a designed compliant mechanism that can take very small forces and give you the displacement you want.

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So, the design of the Micro-Newton force sensor described in these two; no in this paper mechanics based design where we have only static forces are concerned, this is not dynamic force. The femto tool sensor can measure over a wide bandwidth above frequencies the force is changing, but this one is more under static conditions; about 100 hertz is what we can reliably measure using this sensor.

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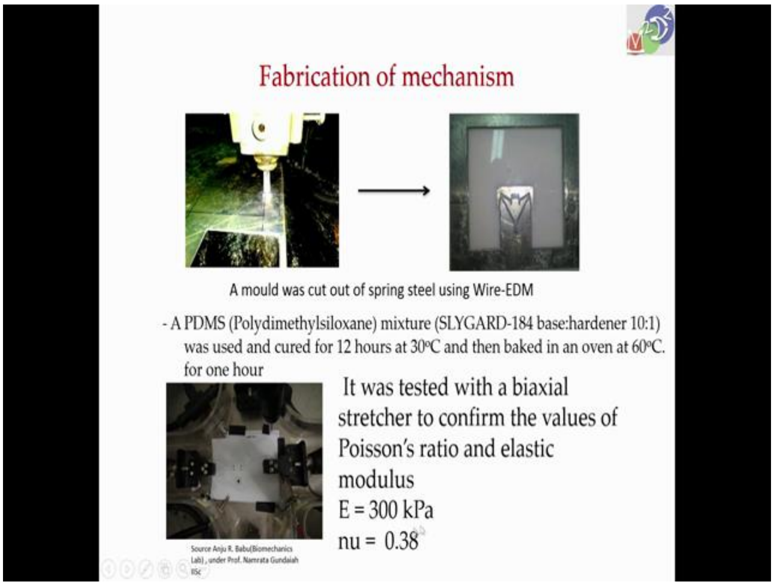

And fabrication is all normal workshop; you can see the workshop things here. And testing using biaxial module modulus machine so that we can measure the properties of the material that we have, here is a mould made using aluminum or spring steel and PDMS is the material used which has a Young's modulus that is quite low over 300 kilo Pascal's. So, with that one we are able to make this one is a mould we can make as many as one need.

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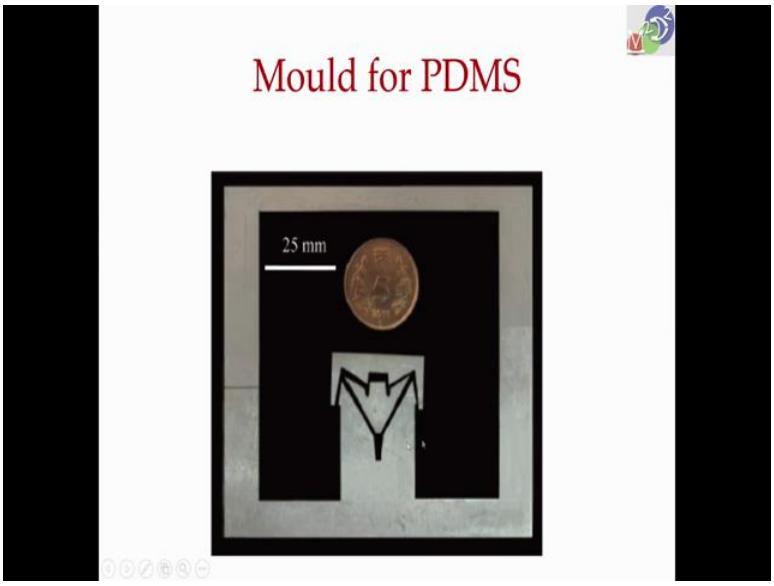

So, this is the one that is the mould for it and you can again see the size 25 millimeters, quite large that 28 is what we had seen and you can make these things.

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And as I said this is like more works more like a cartridge, where the middle one is the one if it breaks you can replace. There is a little holder to hold a glass probe, glass needle or pipette as it is called to attach to this that is one is going to fix and probe the cell to apply force.

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So, that is now we see this probe holder to that you will attach a pipette. These all with aluminums it is quite big digital microscope will be about an inch in diameter and 4 or 5 inches in length. So, it is a bulky device but can measure very small forces.

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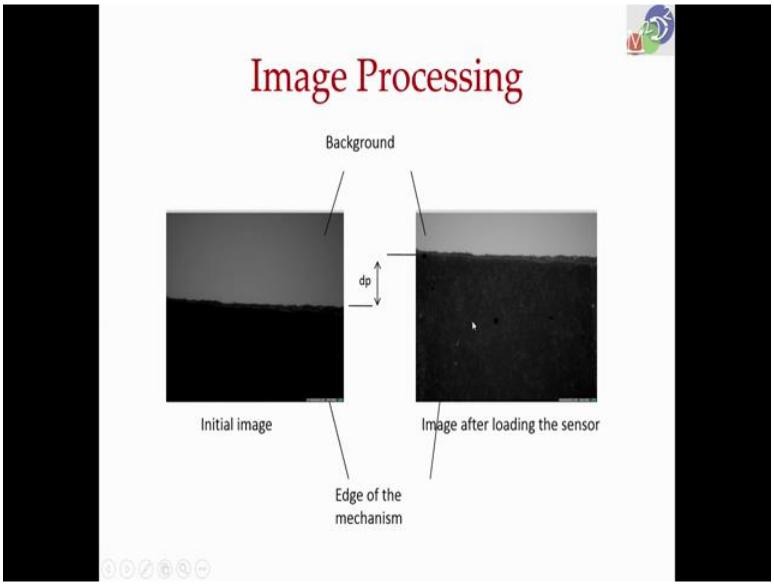

Image processing to see that edge of that output thing, how it moves that needs to be captured and analyzed for the displacement.

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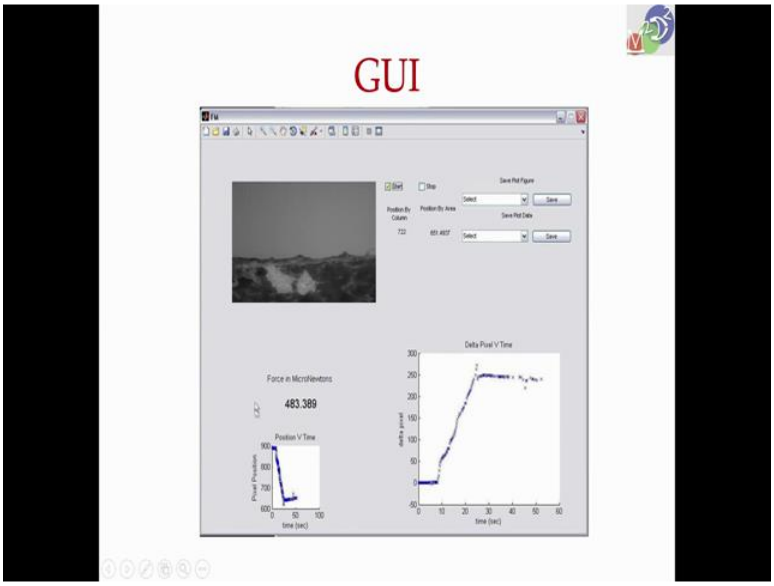

And this is the user interface for it where it will show the force as the function of time, it is a real time dynamic measurement.

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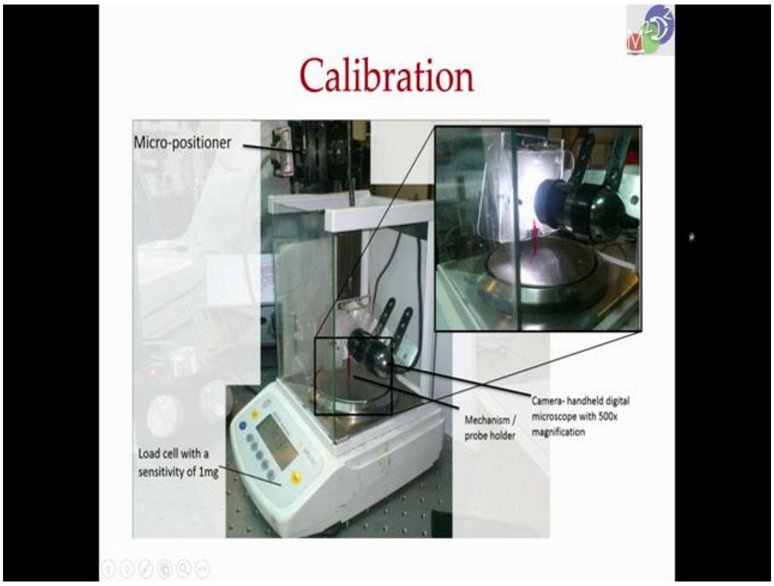

And this was calibration that was quite a task here. Whenever we use a compliant mechanism application you should remember that there will be lot more details, that is what all this case study we will emphasize to you. It is not enough just to design some that has a topology or shape or size and some stiffness beyond that you have to worry about a lot of things. In this particular case study the challenge was actually in calibration. We want to measure Micro-Newtons, but we need to have a sensor that can measure Micro-Newtons and then say that our sensing sensed value is correct.

Here that was a big challenge because there was no other force sensor. What we ended up doing was go to a very sensitive balance and put the probe there whatever this shows and we compare with what we get. So, that is what we have to do. If you think about Micro-Newtons even if you are using like a weight in order to calibrate that will change from place to place because, millionth of accelerate due to gravity changes will be there when you go from one building to another building or even in the same building top floor to bottom floor and different geographical locations. So, calibration here is a quite tricky for these Micro-Newton force sensors.

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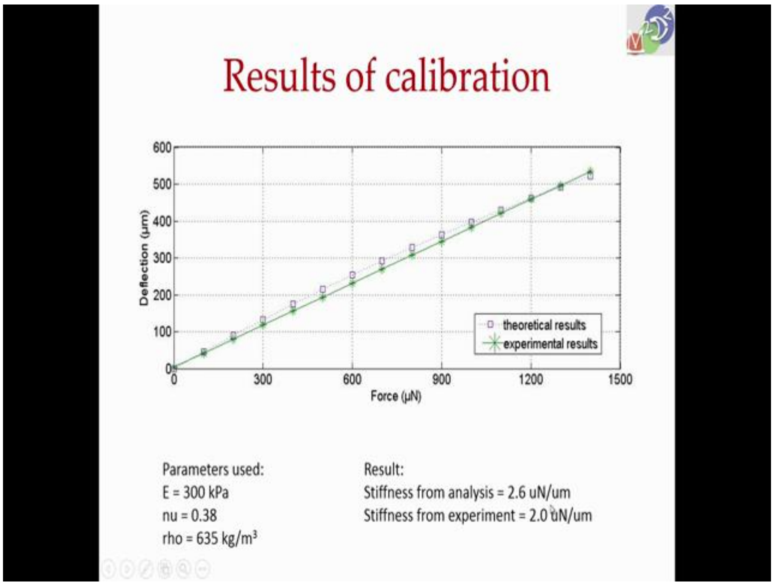

So, here we had some model and theoretical model with finite element analysis and the experimental result measured. And they are linear, they are not exactly coincident, but that can give you an stiffness as said earlier is 2.6 Micro-Newtons per micrometers. And from the experiment we were able to see about 2 Micro-Newtons per micrometer reasonably close; this is theoretical, this is experimental.

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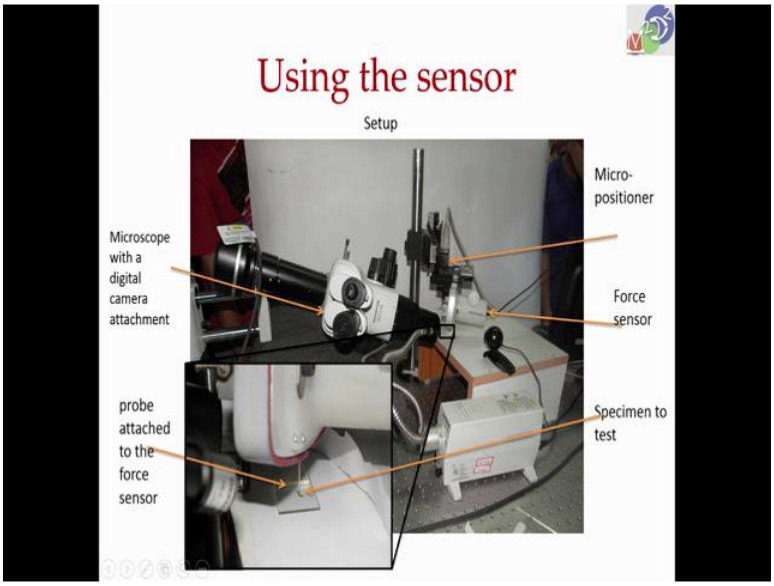

And to use this sensor that is also quite a task; we have this sometimes, we want to go straight up like this sometime at inclined angle it depends on what you are trying to do, so you have to struggle with that mounting as well. And the compliant mechanism is a planar device here. It has to be enclosed in some between two layers so that it does not go out of plane, because that also can change output displacement. So, that was also another thing that was taking into account in packaging this sensor.

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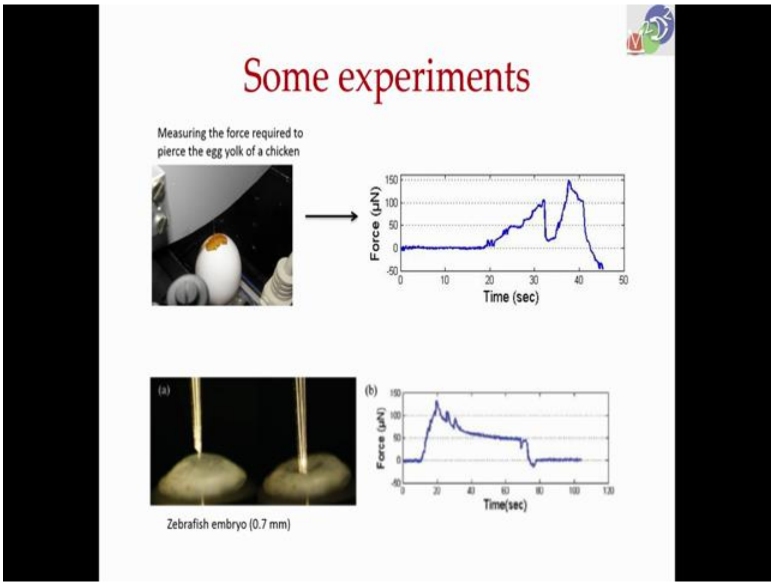

So, initially we took some zebrafish embryos and egg yolks (Refer Time: 21:20) were enthusiastic whatever flexible material or soft material if found started testing that. So, with the egg yolk if you take it has force about 150 Micro-Newtons, this is 150 Micro-Newtons and zebrafish embryo when you are pressing it is more like indentation you can say it went up to 100 Micro-Newtons. Normal cells will be much smaller than that. The force that you apply on them is very small to deform them. These are embryos and egg yolks.

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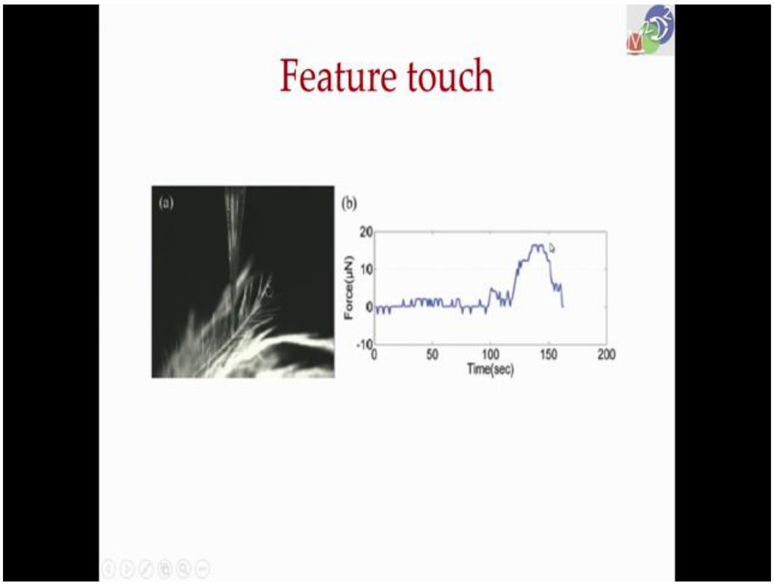

And other thing was this feather. In the feather there are you know secondary feathers, if you touch them closing your eyes you do not feel them. Micro-Newton force is something that we cannot feel with our fingertips. So, even if somebody puts this feather in your hand when you are closing your eyes you cannot tell when the feather is touching you touching your fingers or not. So, we are able to measure that it was about 10 to 15 Micro-Newtons when you push that.

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And I think there is a little video that shows that say one minute we had seen this earlier, but we can observe it from the viewpoint of how this looks now. So, is just to show that there is nothing there is a digital microscope, here is what compliant mechanism is and the probe that is attached there like a pipette. There is really nothing that is all. And this microscope looks at digital microscope looks at the displacement of the output point it is there.

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There are the things you do not feel with your finger, but if you put it with this sensor we can actually see it. The output displacement happening and correlativity force there.

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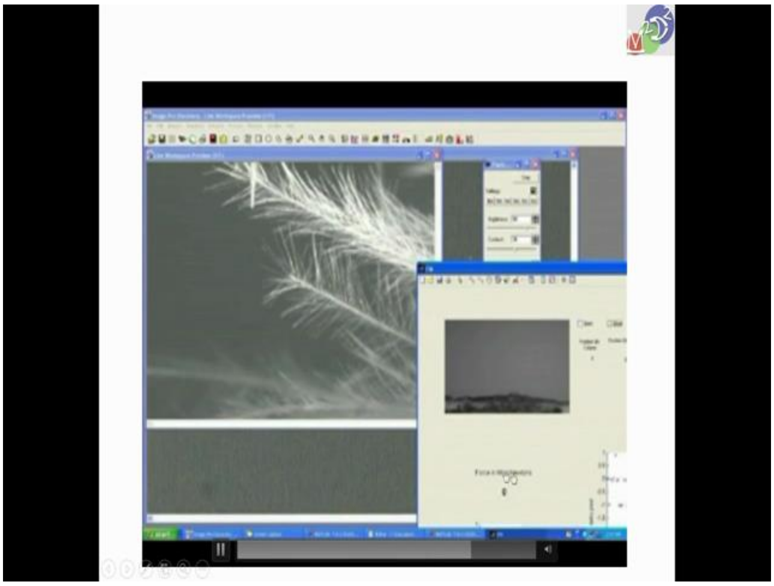

So, when you are pressing the probe and this zoomed in view of the feathers you can actually see this moving so slightly and the value of the displacement changing over here.

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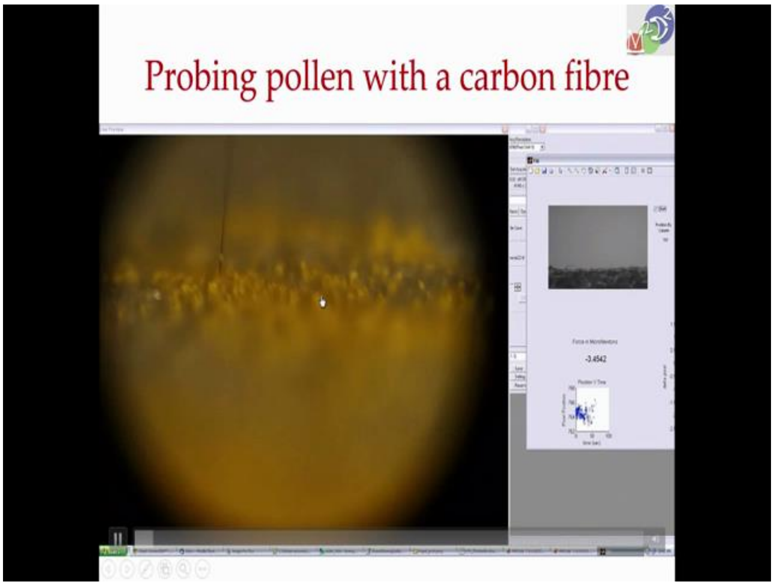

And we also did with carbon fibers and pollens and you know so forth. Like here it is carbon fiber kept and that is what you see the chip here; pollen which is very small when you probe it what forces you measure. It is moving over slightly and you can see the value of that 4-3 Micro-Newtons and so forth. And we can see there is a noise here as we talked about there will be noise, but whenever there is a big jump you know we can see that now we pressed.

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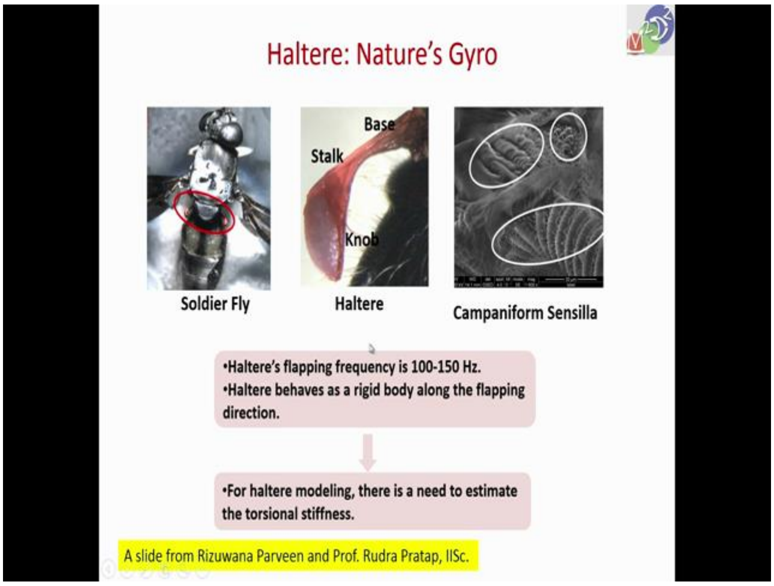

And this also used by people in IISc, because they could not get any other force sensor. So, commercially that works for this application. This was one of my colleague Rudra Pratap’s student doctor Rizuwana Parveen; she is in Singapore I guess now. They were looking at this Haltere that exists in soldier fly there is a modified wing which this insect uses like a gyroscope to know the angular rate here. And they wanted to know the stiffness of this Haltere. So, this is a insect soldier flies like any other small insect and there is this Haltere in bright red colour and they wanted to know the torsion stiffness of this.

So, they wanted to measure the stiffness. So, they have to take this soldier fly probe it push it here, measure the force, know the displacement in this sensor Micro-Newton force sensor. We not only measure the force, but displacement is also available to you. We are measuring the output displacement; from the output displacement we are calculating the input force. In the same process we also know the input displacement. So, we can actually give the bulk stiffness. So, the stiffness how much force is applied, how much displacement we can get and torsion stiffness of this beam that is also compliant in a way this technique they are exploring to make a gyroscope. So, for them to understand this, this sensor was useful.

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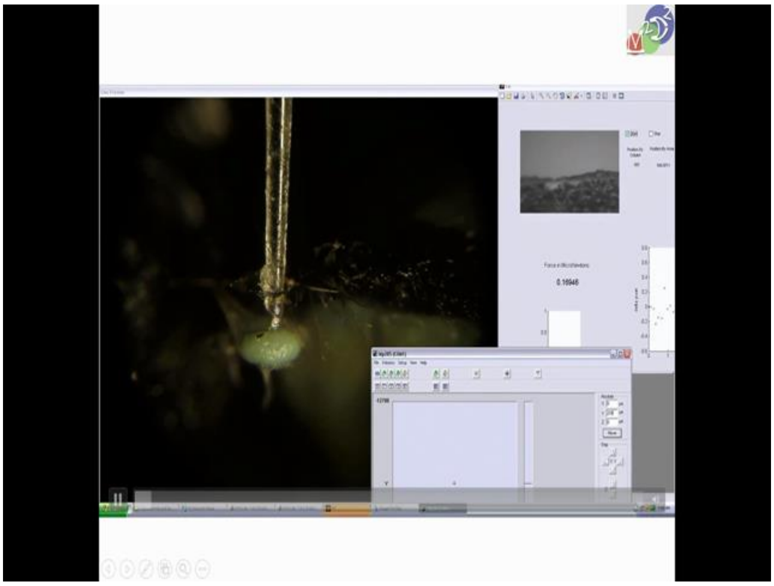

So, I will play this movie to see how this Haltere was moved; so it is being pushed down and the force changing here. So, you can see this clearly the output of the compliant mechanism is changing the image processing, this interface will show you. So, this was used there.

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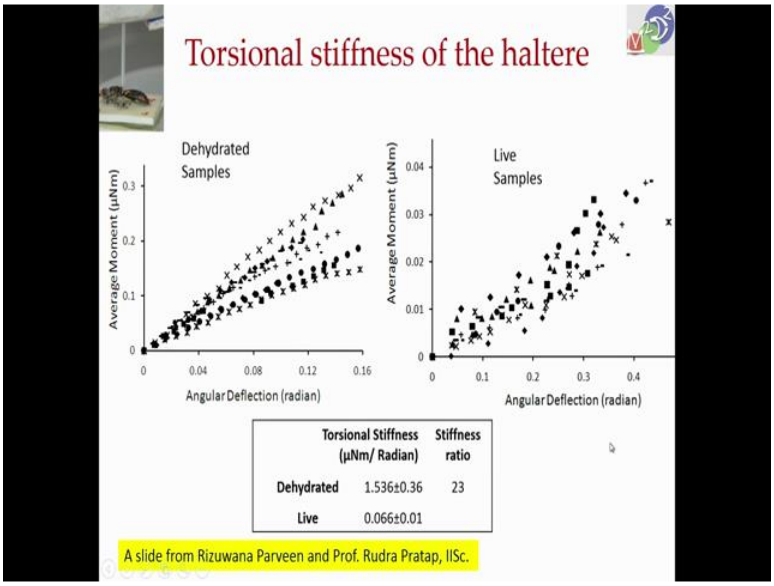

And lot of different samples: dehydrated, live samples, hydrated. So, some insects were I guess used in this study, so many insects as you can see. And the linearity of the moment that characteristics with the force angular deflection calculated from the displacement they were able to get the torsion stiffness that they wanted. So, this can be used by others this sensor because principle is straight forward.

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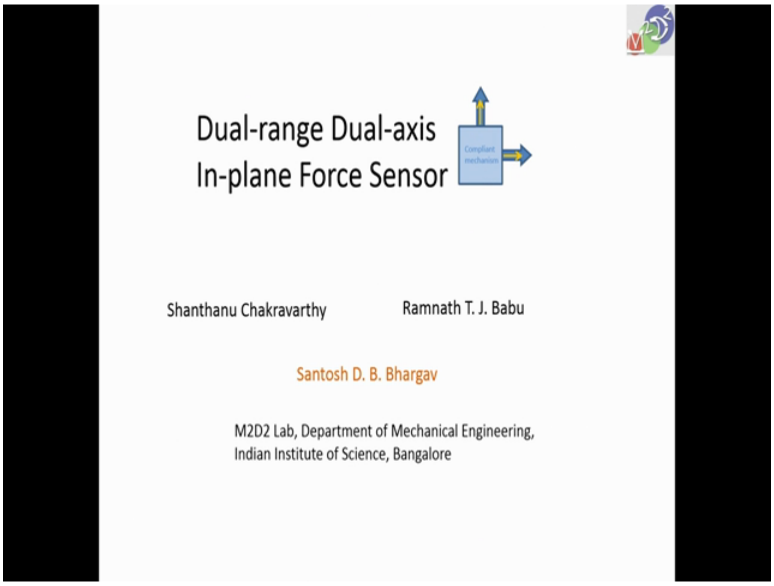

Now, later on all these are former students from our group Shanthanu Chakravarthy, Ramnath Babu and Sonthosh Bhargav; they extended to dual range force sensor. Just like we had dual accelerometer, dual axis accelerometer here it is dual axis in plane force sensor. So, when you are moving something the force can come in two orthogonal directions.

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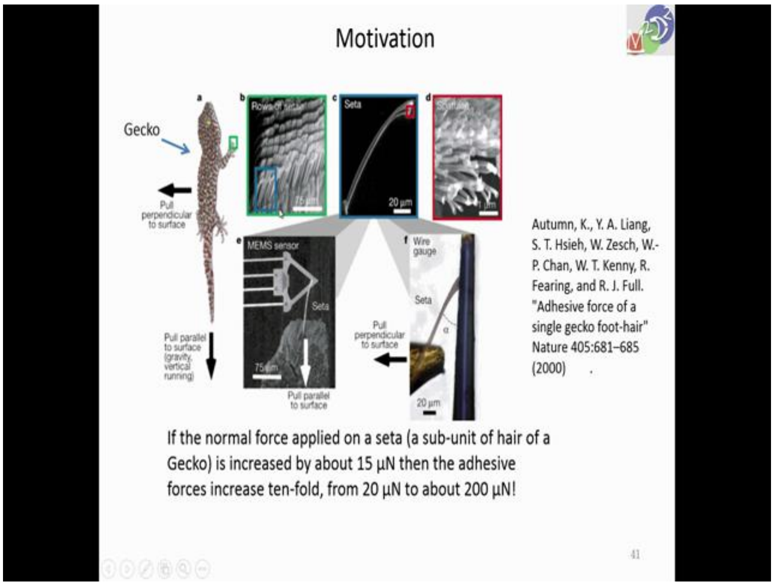

So, they made using a compliant mechanism. They also found out why is it needed, dual you can use two sensors this direction and also to have different ranges, so took another one here that range can be changed with a little adjustment with the mechanism they also got motivated with Gecko which uses the nano structured surfaces the nano structured surfaces to hold on to the vertical walls and go there basically against the few force that is there.

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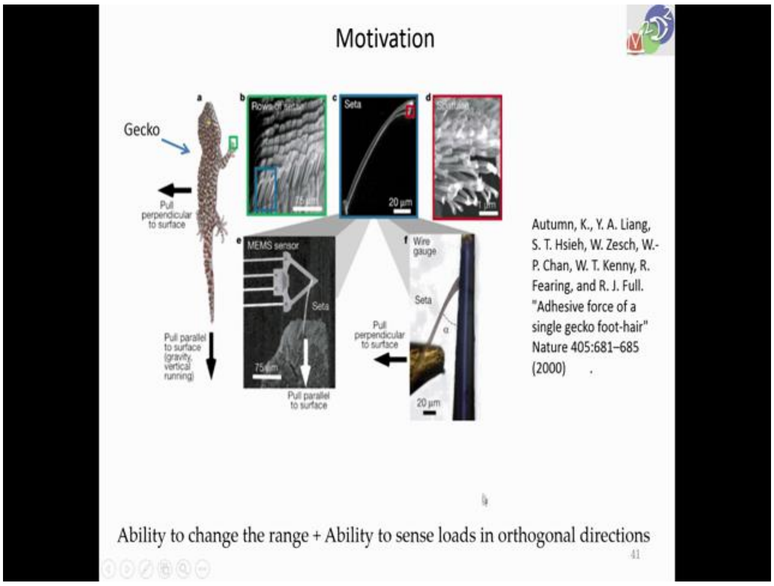

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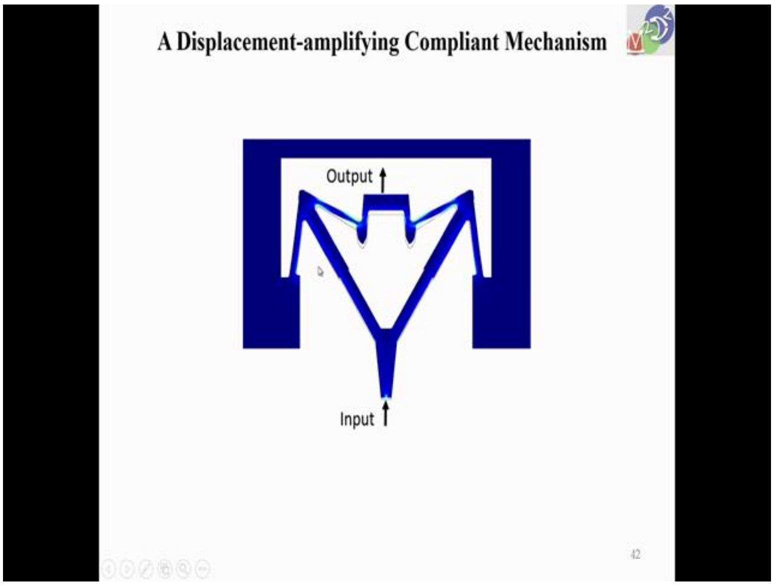

So, this paper wanted a force sensor whose range can be adjusted, range not sensitive resolution.

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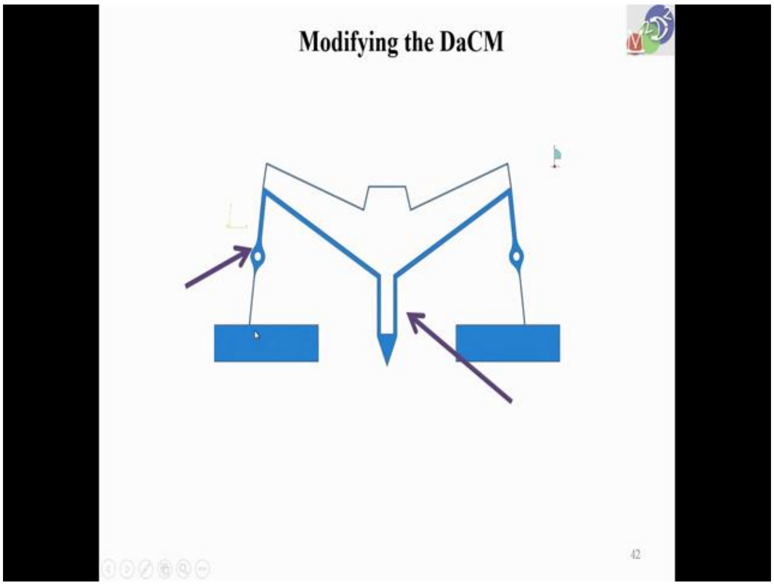

So, they took that thing and gotten two lengths of the beam, when you fix it here you get 1 range when you fix it here you get another range. So, they might adjustable to compliant mechanism where the output displacement can be varied. So, either you leave it open then the fixing here makes sense when applied some force here it will move by something.

Now, when you fix this and fix this the beam length has changed beam, stiffness has changed entire compliant mechanism has changed. Then it can it will take larger force or larger range but sensitivity will be affected, that is what they have done.

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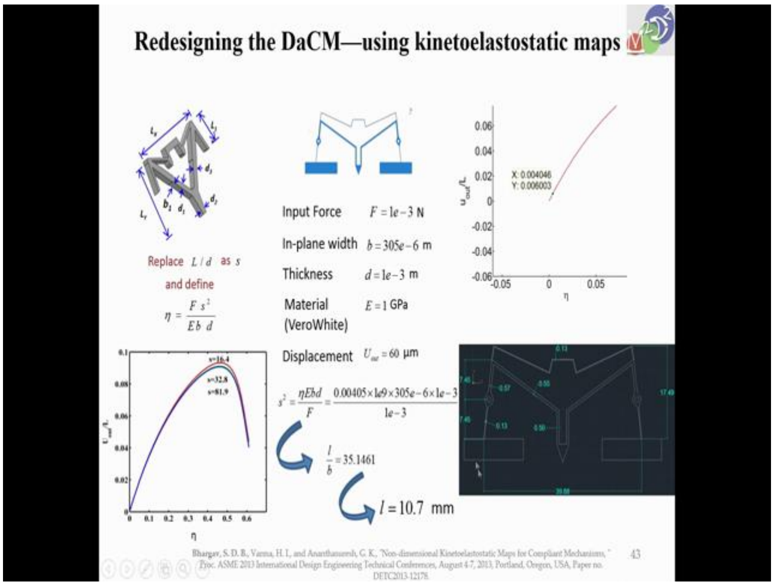

Again in this work also kinetoelastic maps were used to decide the size of it. And the dimensions were determined based on that.

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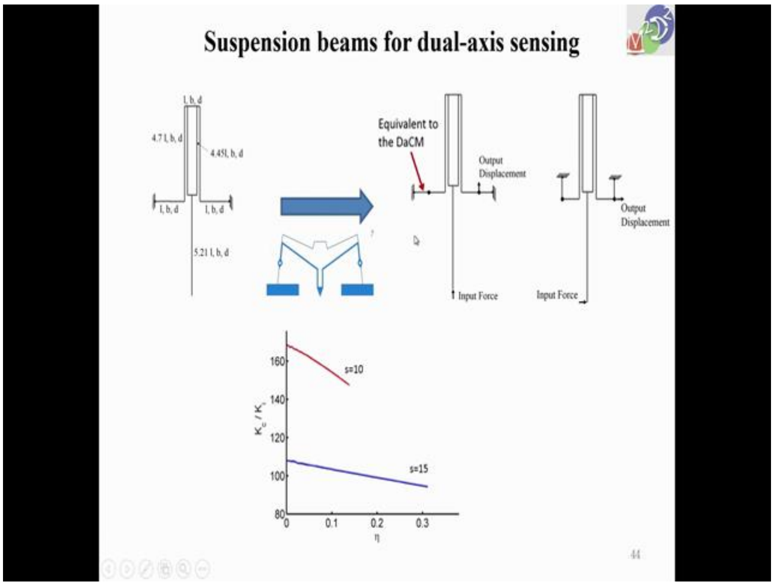

And some more adjustment will be done for selecting this suspension for these things so that in plane it will not move from the place that you do not want to have it moved.

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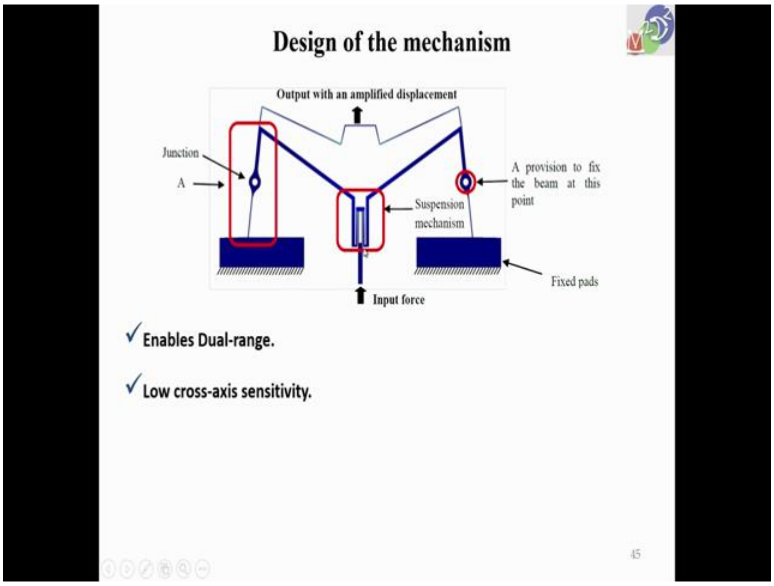

And they put this over here the little suspension as I call it, as I fix it here or fix it here and they are able to enable the dual range and dual axis with low cross axis sensitivity that is. When there is x force and y force you have to really decouple them. So, let us say there is only x force y may still show some reading and that reading should be very small. That should be discounted as noise. And beyond that if you have resolution for y axis or x axis we can tell how much is the smallest change that you can determine.

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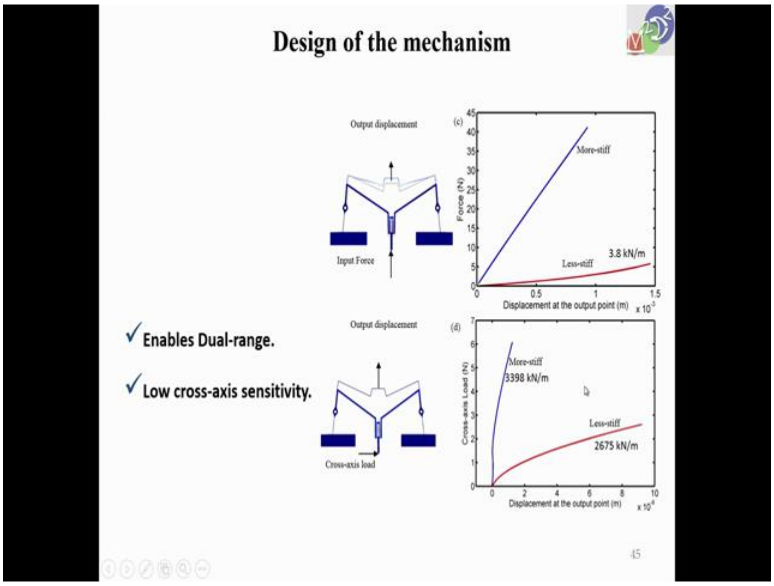

So, they had for both fixing here versus fixing here they generated at this maps.

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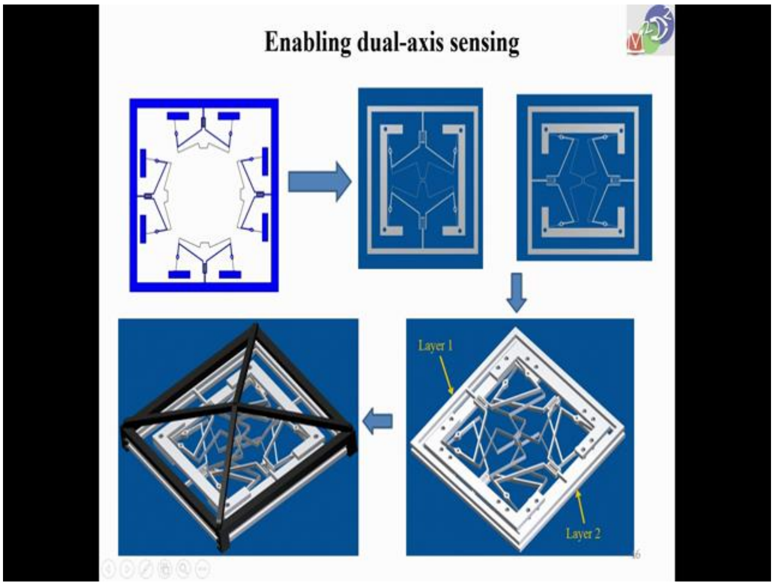

Arrange this for symmetry and made this in multiple layers, so this device. And there was this probe which I attached this is the one that will touch something where it will give you x force and y force separately.

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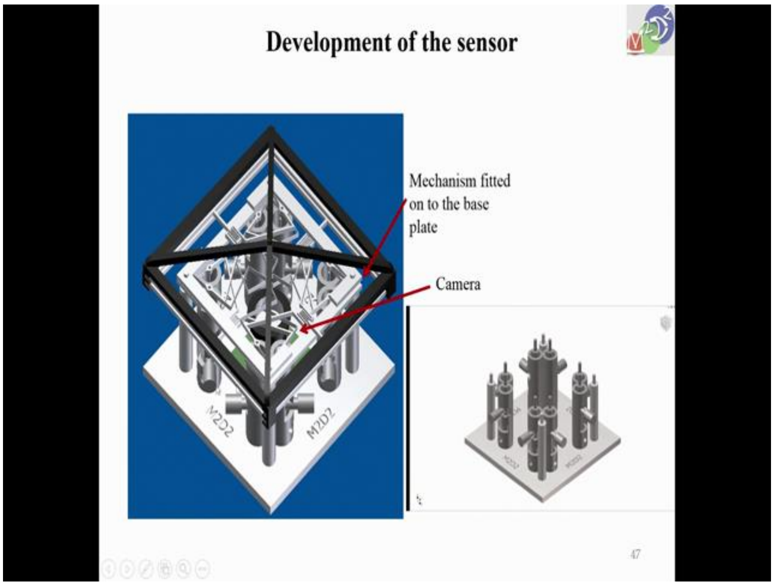

And this is how it looks this all still solid model.

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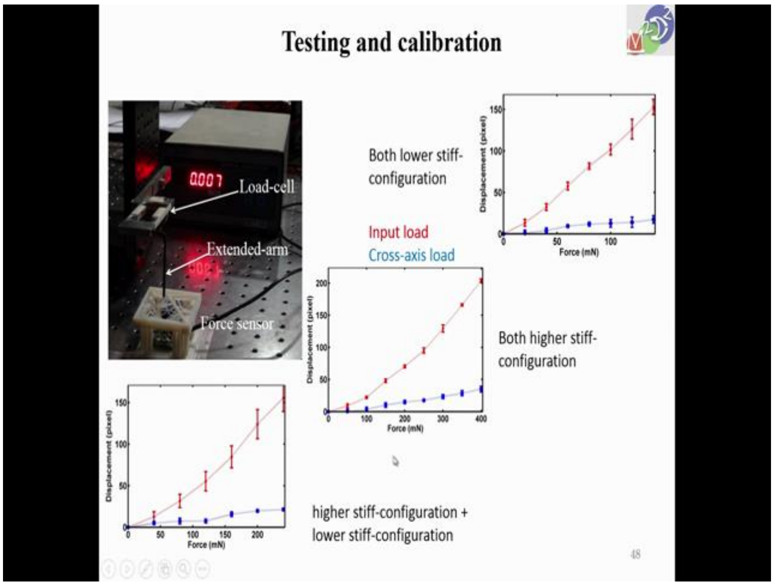

And this is the real device that you see there. And there was a load cell for calibration here this is not Micro-Newton here it is more milli Newton there is load cell to calibrate this. This is quite non-linear, but with affect it can be made linear also this is displacement versus force.

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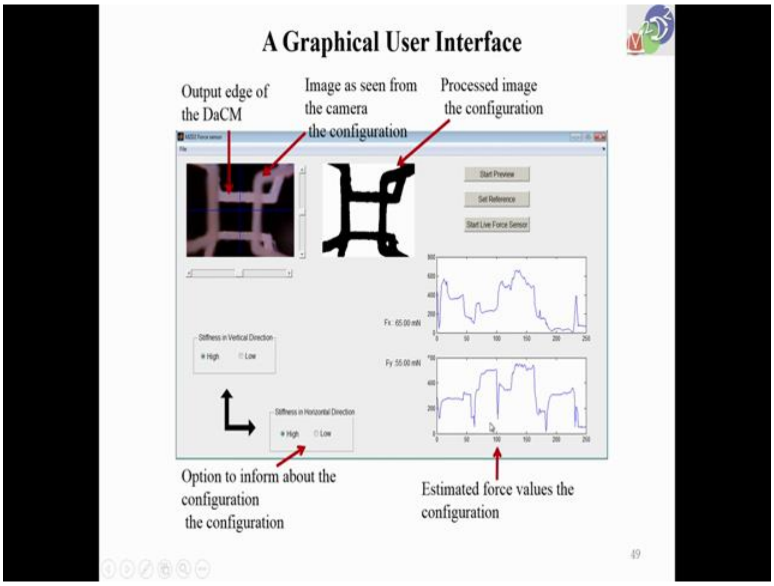

And this is a graphical user interface like the last one.

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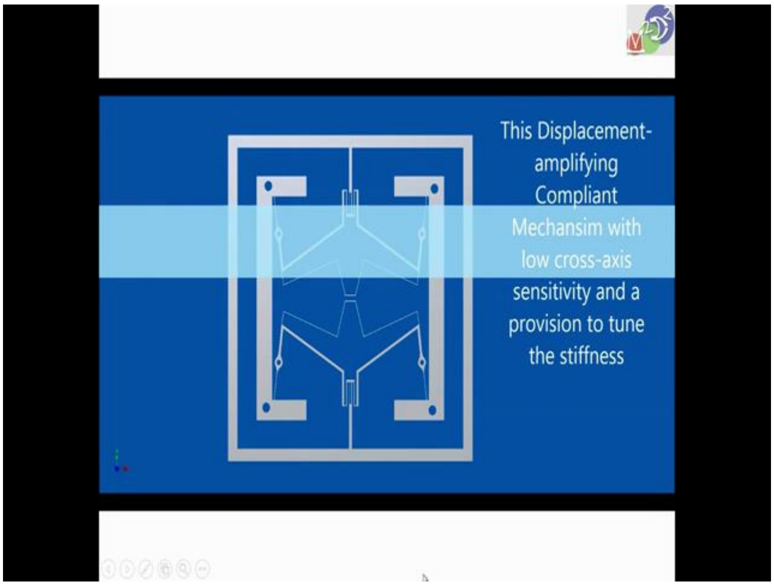

And I guess there is a movie to see how this dual range dual axis works with compliant mechanisms with adjustability.

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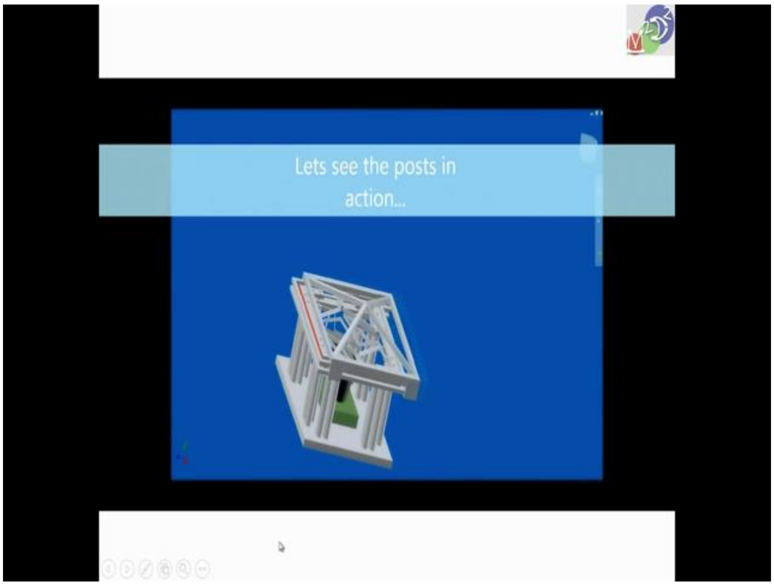

So, these are all the solid models as to how it looks and how it was composed. And how it is assembled different layers and the final layer this is the probe which is what can move x and y.

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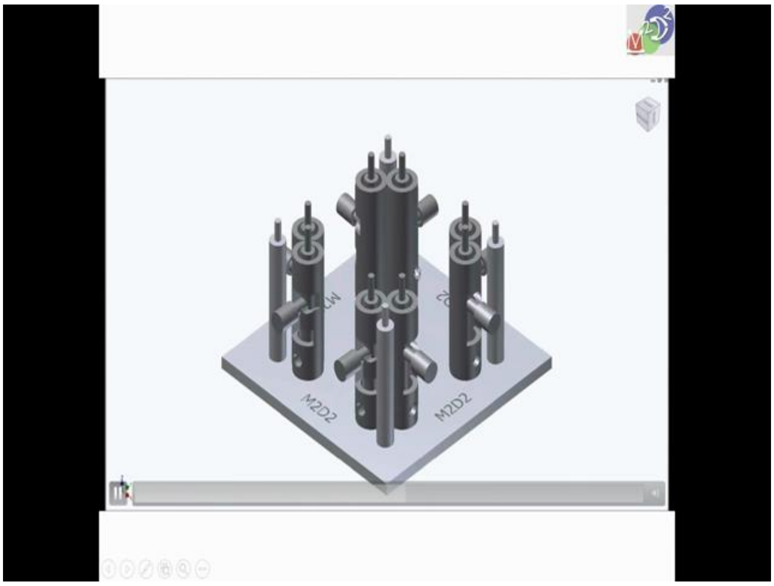

And all the pose and everything adjustment of the spins, so we can change the range of the accelerometer.

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That was that is the prototype; you can see it is big or it can measure very small forces like in plane forces, so the horizontal and two directions in the plane.

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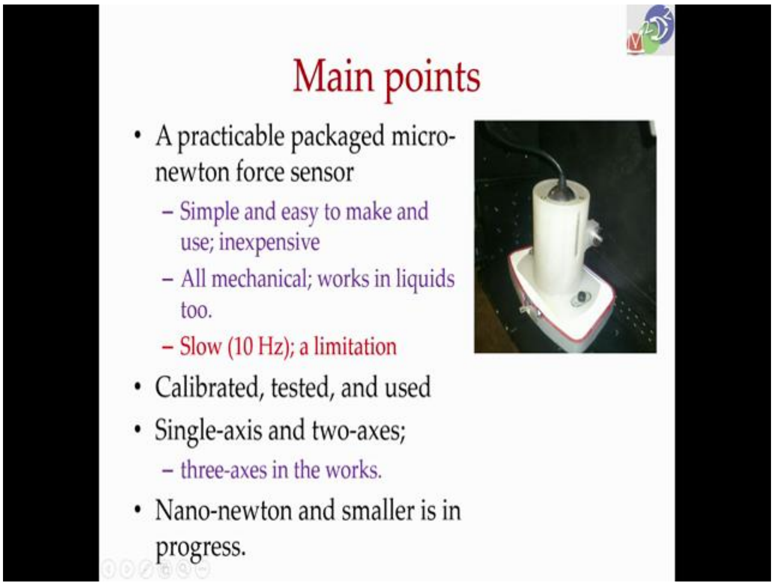

So, the main points of this is that we can actually make a practical or practicable packaged Micro-Newton force sensor using compliant mechanism there is nothing here than the used microscope. And it is slow to 10 to 100 hertz is that limitation, but with some more design we can make it at high speeds also. But the speed limited by the microscope not the mechanism here. Mechanism can be made to have higher resonance frequency, but your frames per second will decide how fast force changing can be detected with this sensor.

It can be calibrated tested, single axis as well as dual axis; one can also extend it to three axis also. Nano Newton levels are also possible, but it all depends on your microscope capability in resolving displacement. And of course compliant mechanism is the one that is going to amplify the displacement over here.

Thank you.