Compliant Mechanisms: Principles and Design
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Lecture – 71
A compliant pipe-crawling robots

Hello, we are going to discuss 5th case study this is penalty meet one, we have 6 case studies total; this is the 5th case study. Here again we illustrate a significantly sophisticated application of compliant mechanisms in building a robot that crawls over pipes externally, there are lot of internal robot crawlers, but this one goes externally and that is what will discussed.

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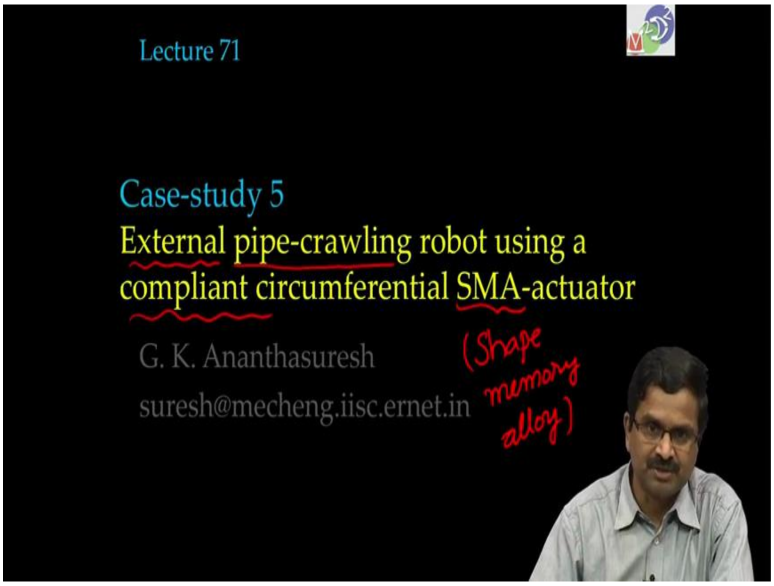

It is actually a pipe crawling robot; it is a crawls over a pipe on the outside that is why it is external and what it uses is a compliant mechanism and it uses SMA that is shape memory alloy actuator. So, in this lecture we understand two things: how to make an external pipe crawling device, and also how to work with shape memory alloy when you are using compliant mechanisms; there are some nuances there, it is not enough to have a smart material like SMA shape memory alloy, we also need to have a work design work with that actuation.

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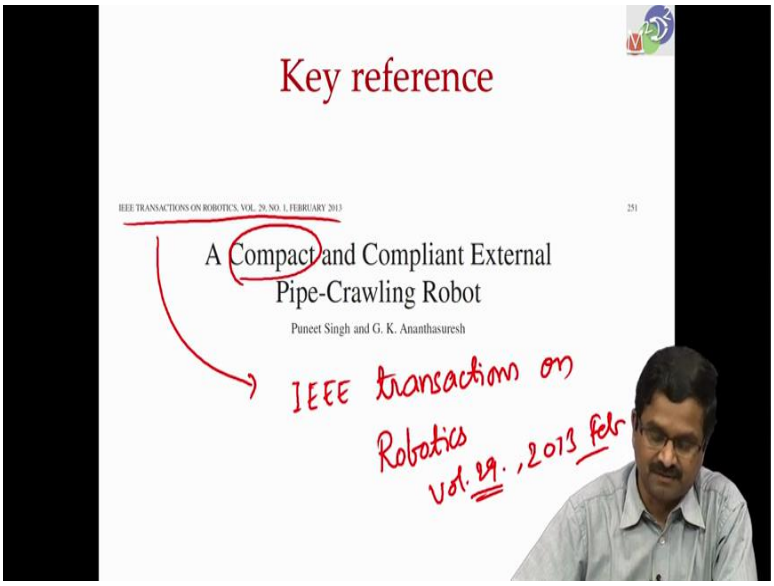

So, here is a key reference for this work, this is small font. So, this paper is from IEEE transactions on robotics; this is volume 29, 2013 February. So, this a compact that is the key feature here, it is compact because of using a compliant mechanism otherwise you could do with a normal (Refer Time: 02:11) linkage also and it is a pipe crawling robot, external.

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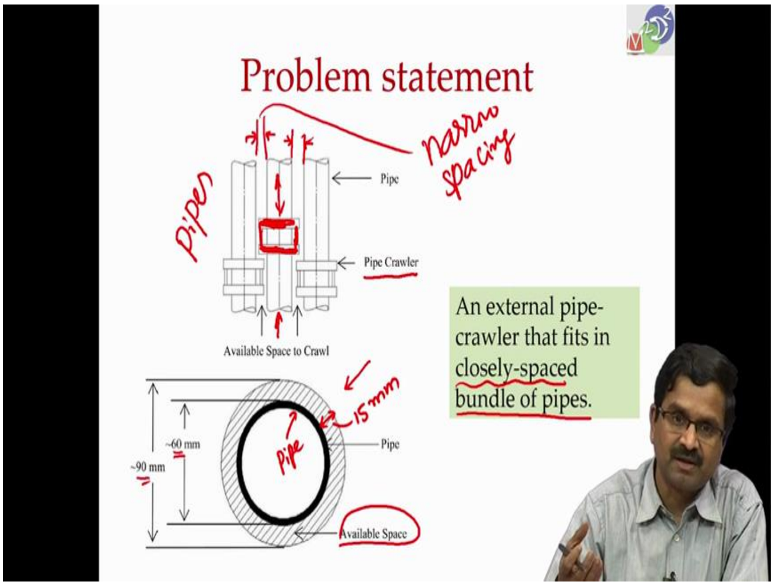

Here is a problem statement - this is something that Bharath atomic research corporation BRC needed it, because they had a bundle of pipes that are closely spaced like this, there are several pipes. So, you can see, there are there is a bundle of pipes and the spacing between two pipes, this spacing is very narrow there is a narrow spacing. In fact, it was about 1 centimeter, 10 millimeter or 12 millimeters is what we were told and we needed something that goes over this pipes to inspect the diameter of the pipes, because when they carry corrosive fluid, it could be eating away the inside of this pipes, so we need to monitor using some ultrasonic transducers.

So, a robot or a Pipe Crawler has to carry this ultrasonic transducers along the pipe, where humans cannot go it had as condition where you send the pipe crawler one hand, it will go and then continuously monitor by moving or crawling slowly along the pipe. The challenge here is that if you see this crawler. So, you let me highlight it, let say we have this crawler is the one that suppose to crawl on the pipe like this, this way, that way they could also bends by the way the pipe can have bends and so forth. So, it has to move and the spacing is the only that much. So, what we need to have is something that looks like this in the; if you look at in this direction where the pipes are there with this go over the pipe, the pipe is showing in this black in here that is pipe and we have only about this is 60 millimeter, this 90 millimeters, we took 15 millimeters either side. So, the space radial space that we have is only 15 millimeters; within this hatched portion that is our available space, we have to design something that crawls.

It can be tethered because the pipes are there and wires can go over them by it has to go within that space, you cannot put anything left features because that space is severely limited here and this roughness of this pipes also quite high because these are all used to carry corrosive fluids. So, they are not smooth and so forth. So, it is should be able to crawl on those things, that is the problem that is the problem statement, this is the concept.

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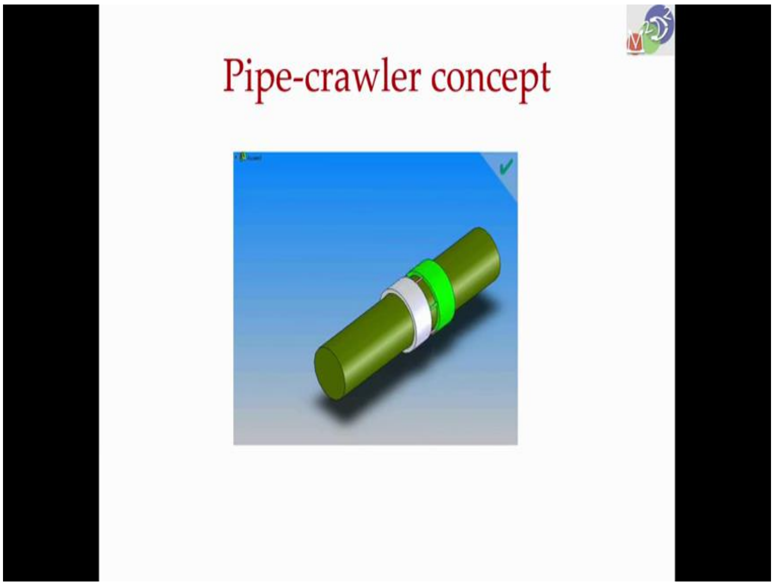

So, this is like a inchworm motion. So, whenever something becomes green that means, that it is becoming loose; imagine that like a monkey would climb a tree, so I have two things here, I rigidly hold the pipe; now when I want to move up I loosen this, I will loosen this and move. So, I loosen and then move and then I hold it then there is a spring here that would bring me back. So, I start here, first both are tight and then I loosen this and there is an actuator that is moves it up and then I hold it tight and this loosens and this goes and that is how it is going to move like we climb a tree as this animation also shows here. So, idea of pipe crawler is this inchworm motion.

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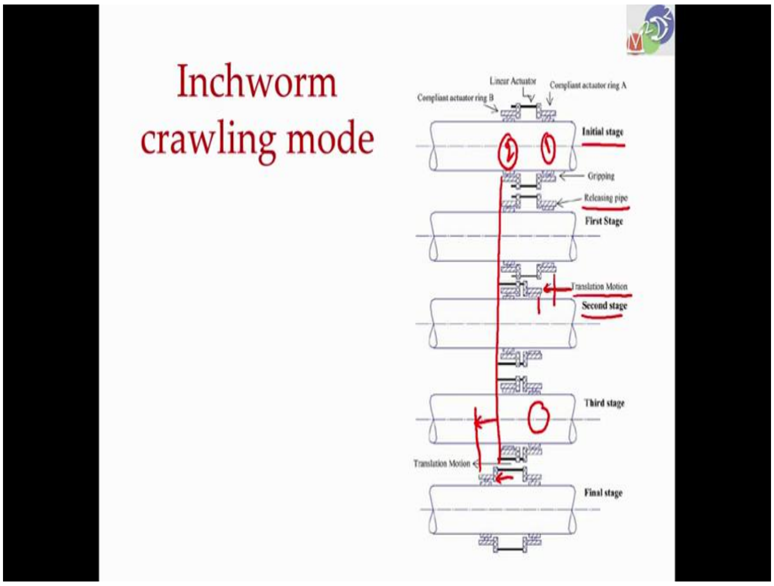

So, that inchworm crawling mode is shown here, there are two rings basically like what I showed with my hands there are two rings, which are both tightly adherent to the pipe and then one of them loosens a little bit. So, this one releases the grip on the pipe. So, both the ring one; this is ring 1, ring 2 and both are hugging the pipe tightly in the first stage and then initial stage.

First stage one of them releases and then there is an actuation that moves them as shown by this arrow. So, what was here it moved there that is the second stage and after that this will tight, this will ring 1 would tightly adherent to this and then ring 2 will loosen; where ring 2 will loosen it will move because there is a stiffness or spring that will make this (Refer Time: 07:04). So, now, we can see where it was and where it is now. So, it has achieved that much of motion, inchworm motion where we hold release, hold release, move and move. So, we initially both are holding one of them releases and moves then it holds other one releases spring will bring it here and that is why need cycle you move certain distance.

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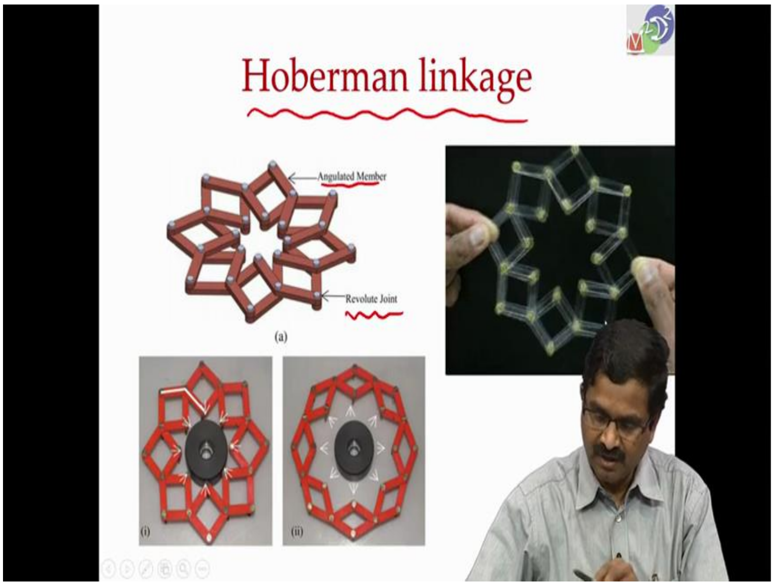

So, in order to hold a pipe and release we went for a linkage this is called a Hoberman linkage, which we had seen there are several revolute joints and there this angulated members here is the thing if you move this in and out, so which we can see here as I am moving this in and out. So, you can see this portion is going you know there outwards, so it is expanding circle and contracting circle, so this is the mechanism.

But putting this on the pipe within that 15 millimeters or 10 millimeters is a challenge; because you cannot make all these joints and we cannot make them really small even if you make them one joint breaking will be a problem and a lot of issues. So, we wanted to go for a compliant design here and in fact, I have a modification of this what you see here. So, what we have here is a circumferentially actuated one.

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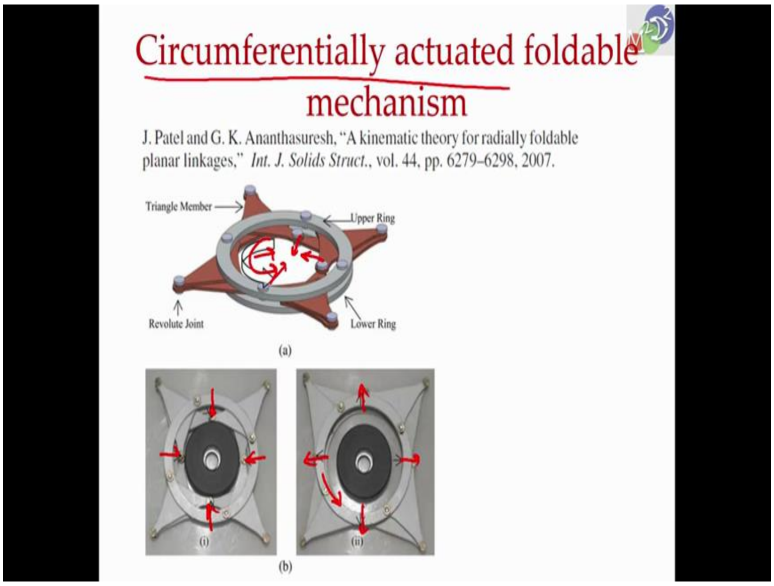

So, there in the previous one as you can see we have to move it radially out and in like this. So, how I will going to put actuate? Because there is a pipe in between there is a pipe as shown with this one here; there is a pipe there so we cannot really have any actuate in two points to move in and out. So, we wanted to go for a something like circumferential actuator, if it is a pipe and we want to go circumferentially.

So, we came up with the linkage that actually has a circumferential actuation that will make the some points move in and out they are like previous one. So, they can move like this or move outwards radially inwards or outwards, but the actuation is circumferential. So, that is the key thing here, circumferential actuated.

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So, I have that device here to show you that it is there rigid body linkage; this is not a compliant one, rigid body linkage and when I apply this actuation circumferential that is I am going to rotate it. So, what I am doing here is rotating this circumferentially to move in and out. So, this particular one we can see how the pattern emerges and this pattern there is a whole paper that is listed on this slide, so where we can chase the pattern, circle if you want expanding circle, contracting circle like the Hoberman linkage that I showed. So, here also I can make.

Now what I am doing is my actuation is circumferential like this, I am only rotating this another side you see when I do that it actually completely closes, completely opens, we can hear the sound of several joints, there are a several joints here. So, there are total of 1 2 3 and there are 8 of them. So, there are about 24 joints in this. So, these not going to be suitable for miniaturization, because you can see when it hugs the pipe and looses grip there are all these things that require lot of space, and 15 millimeters not going to be and also there are this additional decrease of freedom that it has which when we can hear or see. So, there are lots of issues with that.

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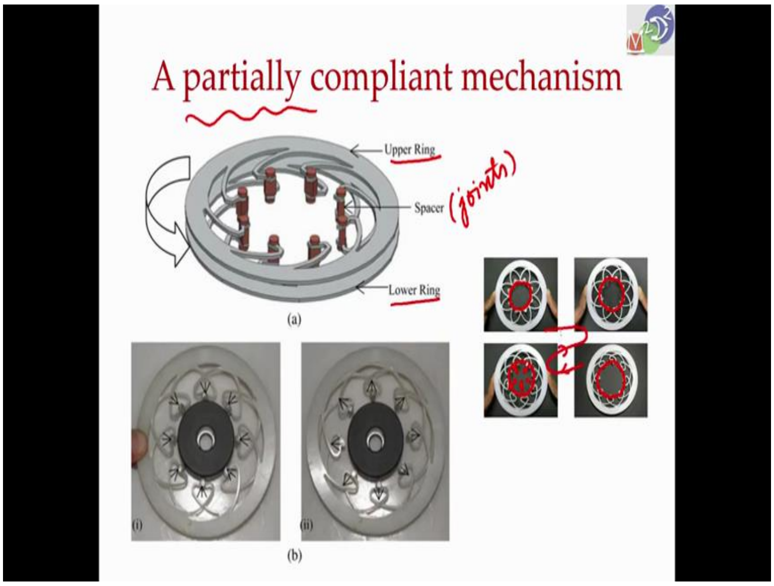

How about a compliant version of that? There is a partially complained version that is shown here which I have the device and which you can see another thing also here. Now instead of those mini joints what you have are the pin joints only here, so there are pin joints 1, 2, 3, 4, 5, 6, 7, 8; 8 pin joints instead of 24 pin joints in the previous one and this actually can go. So, when I am applying circumferential I am rotating one without with respect to the other, this rings this actually in a layered structure just like this was; this also a layered structure, there are actually 4 layers here, now with the complained one we reduced to two layers, and by moving it like this we can make this hug the pipe or release the pipe; hug the pipe release the pipe. So, that is all this is meant to work.

Here we can see that in the slide that we have an upper ring and a lower ring and the spaces are where we have joints, we do not want joints – from 24 joints we reduced it to 8 joints, but we do not want them also, this is still partially compliant mechanism. This one improvement we will want to go towards a case where there are no joints at all so that we can make it very compactly with the appropriate material for actuation.

So, you can see how this gap increases to some bigger and bigger and bigger and then as you release this grip it will go from one to the other. So, here it actually this is the force free configuration, apply force it makes it the move reduce the thing here, the all radially move inwards, all points more inward more inwards so you are applying, more and more force here. So, it is somewhat like this.

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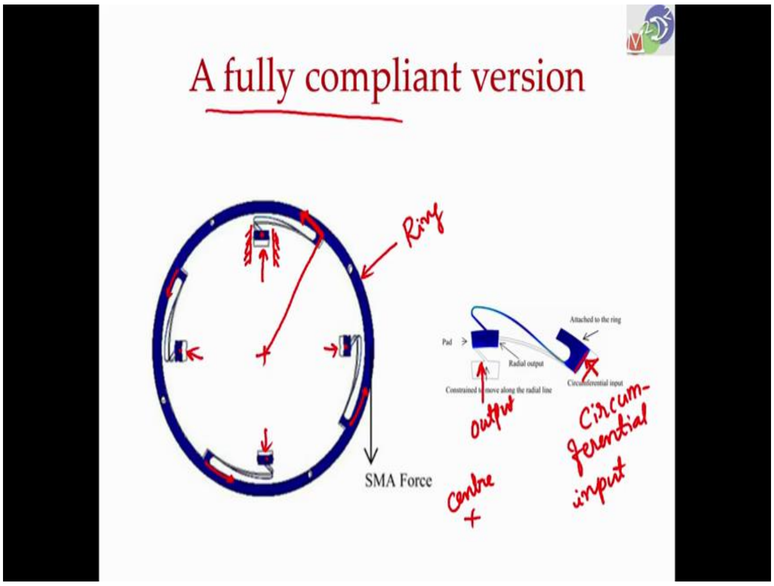

Now, how do you make a fully complained version, that is what is shown here. So, now, we have this ring and there should be another ring and here is where they are going to be attached. So, when this point moves along the circumferential direction in all these cases, when this point moves circular direction these points will move in the radial direction.

So, to see that, imagine that we have circumferential input here by circumferential what I mean circumferential input; what I mean is that we are moving this point along a circle where a center is somewhere here, here is where the center is which is this here we looking at one of them. So, this point is moving along the circumference, it is like a this place like a circle on arc; when I do that, if I have constrained this to move here radial direction that is done with symmetric, we take this ring take another ring flip it like a mirror image and put it on top of that like this. So, there are two rings here, there is one ring the other one is mirror image. So, that is why one has a thing like this here and another one has - now you have to see that one goes like this other one comes from underneath in a direction that goes like this, there are two things which are mirror images of the other.

So, will have a solid model to see this better; so when you do that to symmetry, when you do this, this is going to move like that, so you can see that when you apply the input here the output in this particular case it is not radially inwards, but radially outwards it is going like this. So, when this goes like that this point actually if I do this, this is actually moving outwards like this, so that it will enable us to release the grip on the pipe, it holds and then releases.

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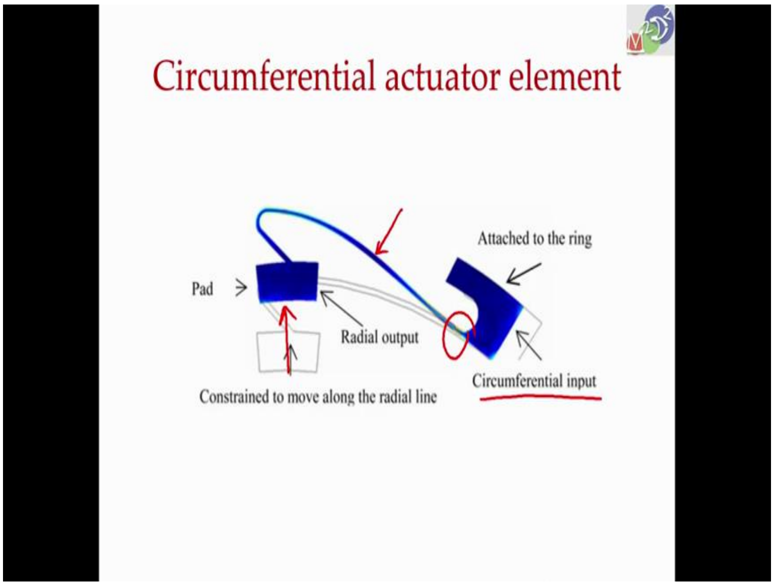

So, here is the closer look; circumferential input and then radial output that is the complained one where you can see the beam how it bends. So, we designed the shape of the beam that was a lot of work, because we have to know how much force can be applied, how much we wanted to retract that decides the gripping force that we have and all of those have to be taken into account and also high stresses that are experienced at this point all those in had to be taken in to account to design this.

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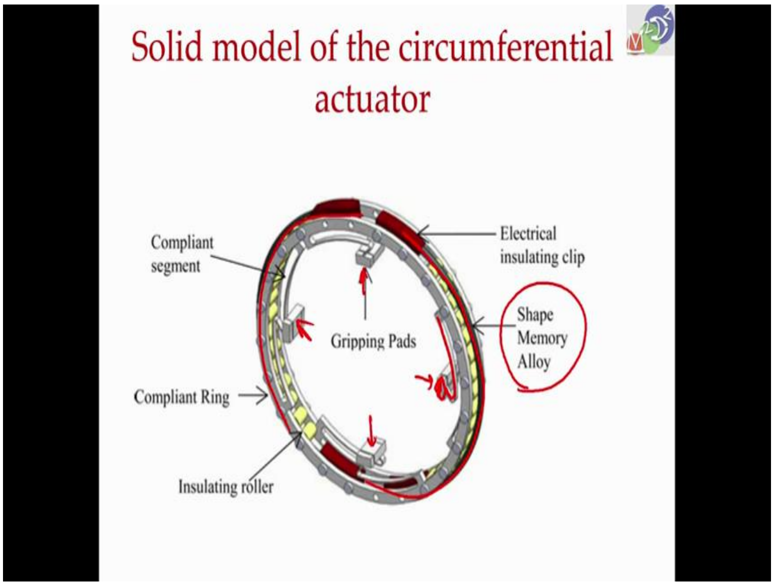

And here is how it looks; you can see that individual thing is over here that we saw. There is another one behind which is the second ring within this that is going to be attached over here for all 4 of them, that it should showing one ring actuator, what is actuation here? Actuation is which shape memory alloy. So, will have shape memory alloy, we put a wire this black one that you see from here to here if you heat it is going to contract that is going to provide the circumferential actuation, whatever we said that we have to move this along the circumferential direction is done by the shape memory wire.

So, we have one wire there, another wire the other side, there is the black one that goes like this they are going to pull this individual 4 segment; you can have 4 6 8 any number. So, gripping pads are shown here. So, any number of them can be done, any number of segment shape memory alloy wire can be put and that is going to do this. When shape memory alloy contracts, it is going to apply circumferential actuation; when you cool it, it is going to the mechanism since it is deformable it will pull it back; back to the original state, so it can go one more round because the inchworm motion or a monkey climbing a tree is a cyclic motion. So, it has to come back original thing and then do all over again.

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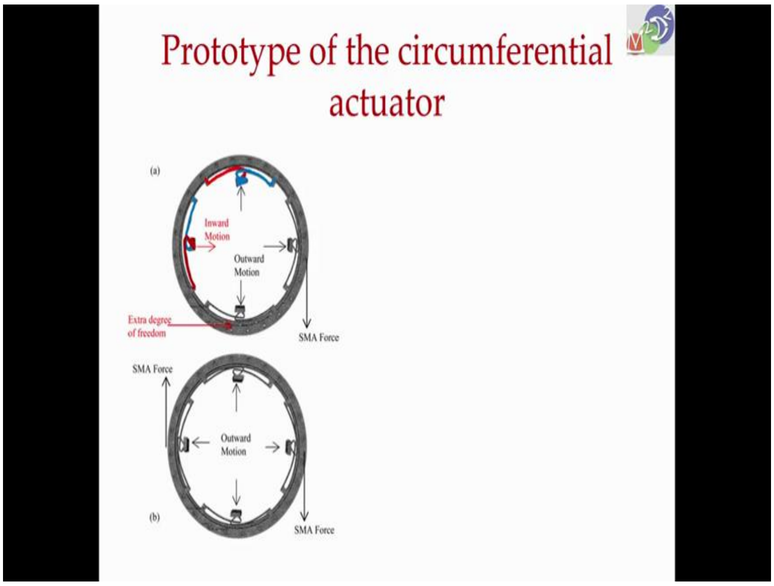

So, here is the prototype actually; where SMA wire two rings you can see what I told about things overlapping. So, one of them is like this, the other one I will do with the different color it is exactly mirror image of that here. So, these two are attached to one another. So, same thing one is like this, the other one it goes opposite, they are both welded here.

So, they are flipped and put, there are two rings here and which is what I have the device here, what I am going to show this prototype. So, here is where it actually made of spring steel.

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So, spring steel device where we have this exactly the diameter or the wire. So, where there I gave two layers ignore the plastic one that is only to put another actuator later, there are two spring steel things here, which are attached at the pads and they are flipped. So, one of them goes one way the other goes the other way. So, we can see one of them like this, the other one goes the other way as the diagnamic is shown and you need to have this is the one that can grip the pipe and then release; grip the pipe and release. So, it is a circumferential actuator, actually there is a SMA wire going through this here, another going through here; when the wire contracts relative to the one, the other one wire I attached to one. So, other one will move like this circum fluctuation then it will release the grip.

Now when the wire cools the mechanism this has deformed, it will bring it back to the other (Refer Time: 19:24), it actuates and then it comes back other time it will come back in grip. So, by having a very compact SMA wire is just a wire and this whole thing as you can see it is not more than 15 millimeters that we wanted, and it can be very long by pipes are long so there is a one ring, another ring this can release and grip, other release and grip between them we can have other actuator and a spring to move it step by step by step. So, shape memory alloy, it is a smart material and we need to understand how to work with it, because it is a phase transformation material, so as you can see in the diagram, temperature versus the load that we are showing.

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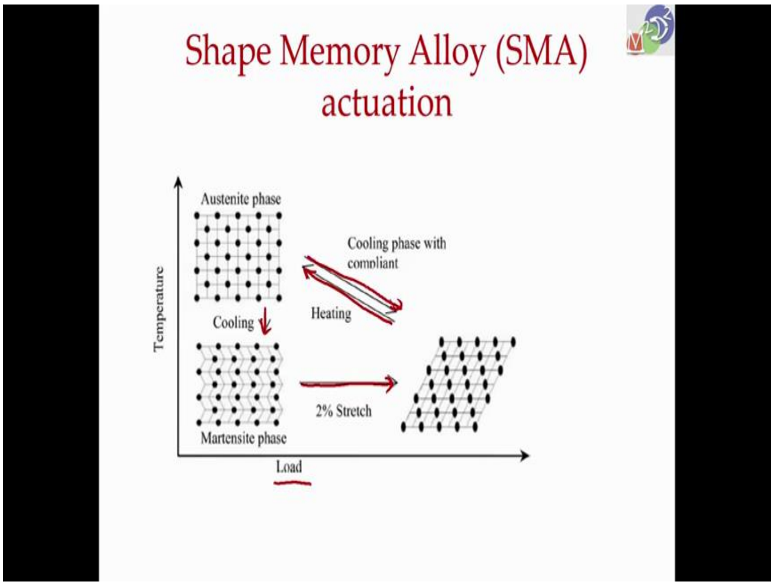

So, it switches between Martensite and Austenite phase. So, first will you heat it when you heat it, it is going to contract whatever is (Refer Time: 20:23) going to contract and then when you cool it, it is going to Martensite phase where if we stretch it, it will be some stretch state and then it will go. This initial, afterward cooling and heating can go back and forth to contract and then mechanism has to pull nobody is going to pull it right. So, if you have shape memory wire, that is in some stretched condition when you heat it, it is going to contract by go in to austenite phase. After austenite phase something has to pull it back, that pulling back is your spring or were compliant mechanism here. SMA wire actuate compliant mechanism when it is heated, when the wire is cool down again it will stay there if you do not do anything, it has to pulled back to the original state, let me illustrate with a diagram.

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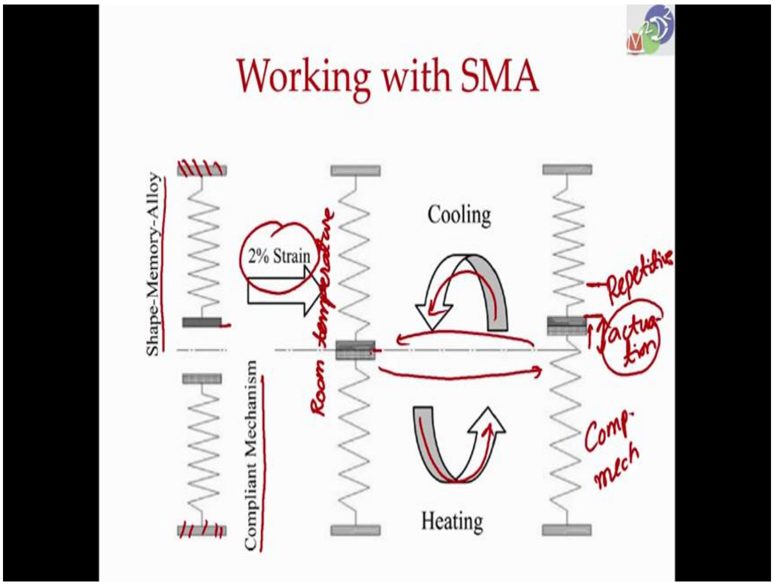

So, here compliant mechanism is represented like a spring and so if the shape memory wire as another spring; both have their own stiffness. Only thing is SMA wire also has the actuation capability. So, what we do in the beginning is to get these two attach them when they are attached, they come to some kind of equilibrium the displacement here and here need not be equal. So, it depends on the relative stiffness of the SMA wire spring and compliant mechanism spring, they will have some equilibrium at room temperature this at the room temperature.

So, you take one and fix them at some point, now you apply force and bring them together to come some equilibrium and after that so at that point in this particular thing that we have usen or you have used that has 2 percent strain, now when you heat it what will happen is, SMA wire is going to contract. If this spring that is compliant mechanism is not there, it would have probably gone up to here, but now it has to pull the mechanism also it has settle at that point itself. So, what was here I was pulled, it came to some equilibrium with this spring, now when you heat it, it went (Refer Time: 22:50) the spring were not to be that gone a lot more, now it cannot because it apply force it settles somewhere. Now when you cool it, what we want is that to come back to this position so that we can repeatedly go heating and cooling, so we can have this much of actuation, this is our aim to actuation; repeated actuation, repetitive actuation.

So, we are heat it, cool it so the mechanism has to have sufficient stiffness to pull it back after cooling and the actuate should have the sufficient force to pull it, by that actuate it displacement whenever you heat. So, you have to design the mechanism in accordance with the stiffness (Refer Time: 23:39) actuator as well as this force capability.

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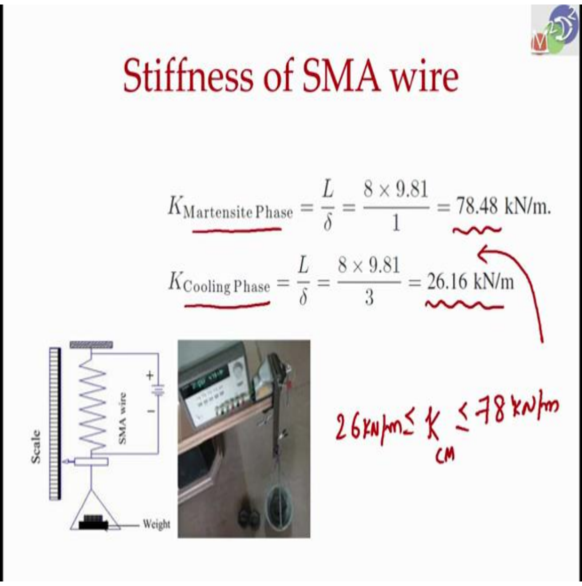

So, what we did was SMA wires that we have they actually did experiment to see what is the stiffness in the Martensite phase and what is the stiffness in the cooling phase, the austenite phase. So, here we saw that stiffness is 26 kilo Newton per meter is 78.48 kilo Newton per meter. So, we want to have compliant mechanism stiffness in between these values. So, upper limit is 78 kilo Newton per meter and the lower limit 26 kilo Newton per meter so, here is where compliant mechanism stiffness should be there. So, it should be in between; so that you can go both way that is, if it is very stiff SMA will not be able to pull it, should be some value and cooling phase if it is again compliant mechanism stiffness is lower than that, it would not be able to pull it back. So, we have to pay this attention to this detail in designing compliant mechanism.

Here is where initial design that we have talked about circumferential radial that is more of a functional feature that is what we have discussed with the design features alloy, design techniques alloy; but now we also need to worry about the strength that goes without seeing, but additional stiffness a particular value that works with is SMA wire, that was very important in this project.

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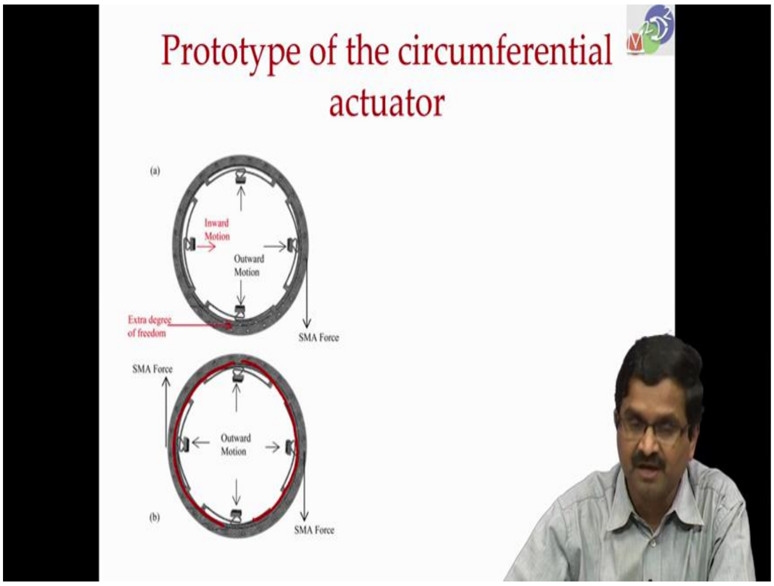

So, when we do that when we have the SMA wire these things should move and in fact, when we sorted it out for each of this actuators we had 4 quarters of SMA wire and all this electrical connections because this is we have made with spring steel and SMA wire cannot touch this. So, we needed to put some insulation, where SMA wire because we heat it by passing electric current through it.

So, we cannot short circuit it because this is spring steel; where you go for spring steel? If you went for plastic first of all it is hazardous nuclear environment, plastic may not survive rather is that they do not have enough stiffness to apply gripping force on the pipe. So, only something like steel or metal will have enough stiffness to apply enough force on the pipe to grip it, because the pipes can be vertical, horizontal, bends and all of that we need to go for spring steel; where spring steel we have to go, then we have this problem of electrical insulation that needs to be done for a SMA actuation; we need all that when we put 4 segments; any little misalignment in this 4 segments, it will make this mechanism not everything move really outward, it will also moves sideways.

So, because it is a compliant mechanism there are no sliders to ensure that it is moving only in that radial direction, it also you can move; any misalignment, any asymmetry in assembly was causing problems. So, there where lot of issue that needed to be sorted out and the stiffness in the other direction, what we call cross axis stiffness had to be taken care of so that under this circumstances these pads move only in radial directions upon the SMA actuation. Instead of 4 SMA wires, we ended of using only two by putting two of them together here, two of them together in an arrangement, so that with asymmetry misalignment we kept it to the minimum; there all the detail that are also explained in the key reference paper that I showed at the beginning.

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So, now we have ring 1 and ring 2 and in between we have another SMA spring and a bias spring. So, this is the one that these two are gripping tightly, one of them releases then the actuate will move it down, SMA contracts this SMA spring here will contract will come down and then this would grip it tightly after moving down let say it has moved here, now at this point it grip it tightly then you release it and this other spring that we have they will move it here. So, what was here would have moved down. So, there is a gripping release, gripping release in between we have leaner actuate, translation actuator and then the spring moving. So, both are gripping this releases and moves down and now the actuator will move this down and now this will grip this will release and this will come down. So, we can actually do this step by step.

Let me show you one more time both are gripping, now the bottom one releases; when it releases we had actuator that will move it like this, afterwards this will grip and this will release when this releases this spring between them will move it down so it are come to another state, that is how it will move one by one by one like inchworm motion, that is what we have the actuators and bias spring here, they also have to be done in same way that I described. So, one of them should be able to compulsive; that is the spring that we have the bias spring should be movable by the SMA force and when SMA actuator cools, it should be able the spring should be able to move it back to the original state. Just like what I showed for circumferential actuation also, that is something we have to remember when we use SMA wire or a SMA strip or any SMA or shape memory alloy actuators.

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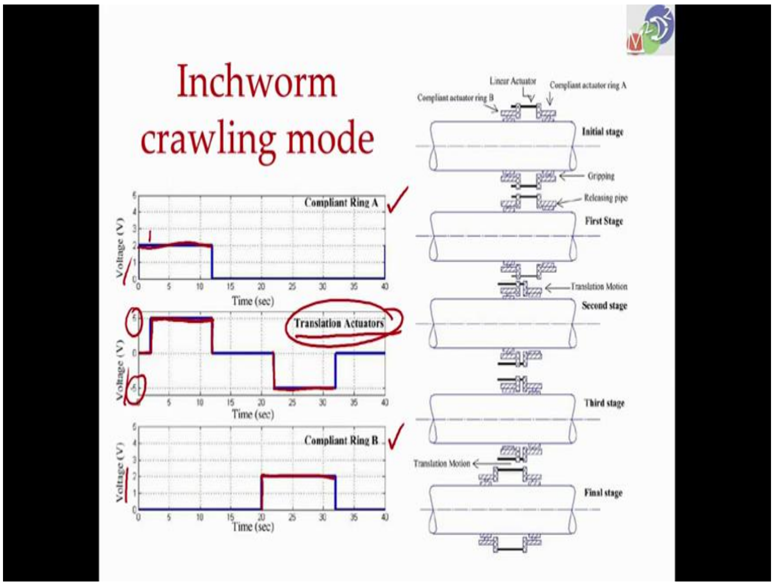

Inchworm mode that I just described with my hands, that is here and that needs to have voltage applied this is the voltage applied for each of this. So, we have compliant ring A, compliant ring B and then there is translation actuator in between. So, initially we take compliant ring A to voltage applied, and other things are not there, when you release that we also are applying the translation actuator after little while. So, there is a little delay after that this is there that is 5 volts and then that comes down.

So, at that time the second one after little while, the second one second ring actuates and then the translation actuator again has a negative voltage to move that back, here what we have done is instead of using SMA for translation actuator, we actually used a DC motor that is why plus 5 volts and then minus 5 volts reverse in the direction. So, it moves like this, moves like that instead of SMA this one is showing the translation actuator is a DC motor as you will see in the prototype.

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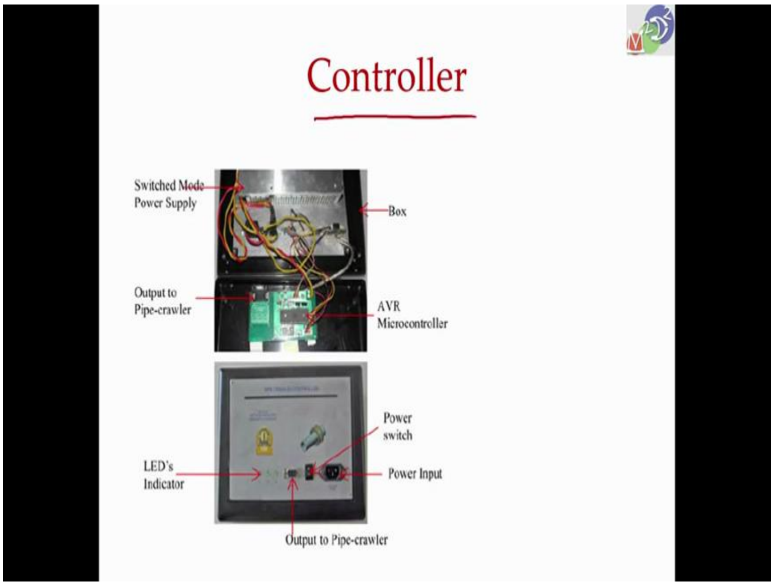

So, for that you needed a controller, because there are 3 actuations now. So, the controller was built and attached to this pipe crawling device. So, what we have here is this DC motors.

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So here what we have not a SMA one now in this prototype we have done a SMA also, but that became difficult, also slow because SMA has to be heated and then cool down and you do not get much motionly, crawling was really really small, so with that DC motor is good; because holding, grip tightly and release in between the translation actuator would move here.

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These prototype and here you see it is holding against gravity so we have the pipe here this was applied by the (Refer Time: 31:11) and it is holding by itself and now when you apply actuation, it just felt down because of gravity because gravity is there clause the grip and fell down.

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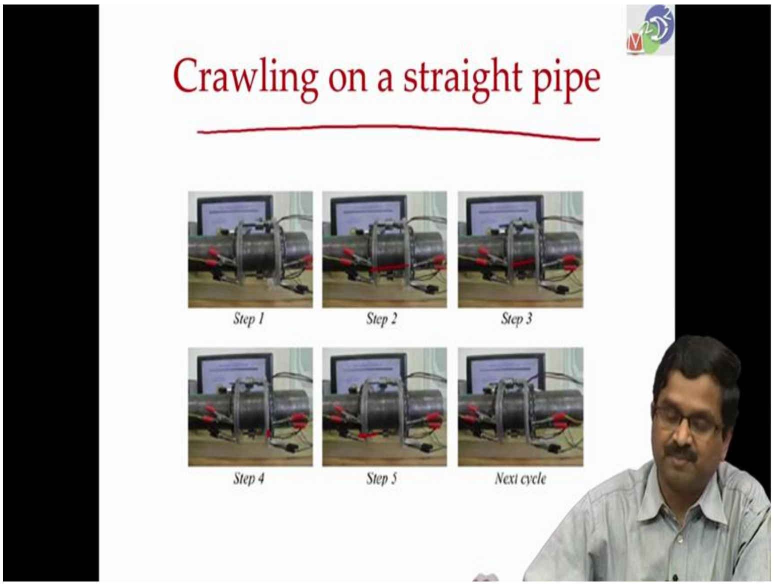

This is one ring and here is where we have the crawling taking place on a straight pipe we have the pipe, we can see the thing it is step one and then step two will releases and it has moved, so this gap has reduced and then second one this holds tightly now and this releases, so this has moved that way and then it is goes on next cycle, will keep on moving on a straight pipe.

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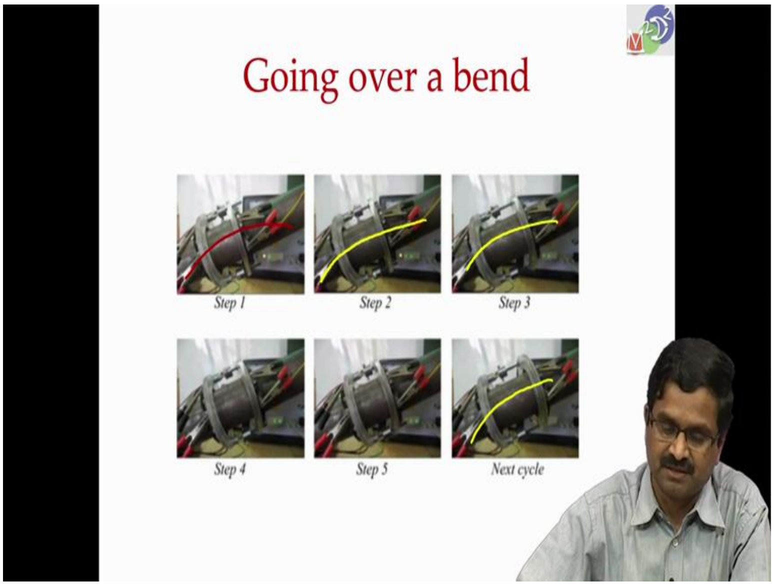

Now, we also demonstrated on a bend pipe also, here is there is a bend in the pipe and over there also it can negotiate because this is compact; if it not to be compact it would not be able to do this, ideally it will probably need 120 degrees, even 90 degrees if you want and we have to make it even more contact to make this actuator.

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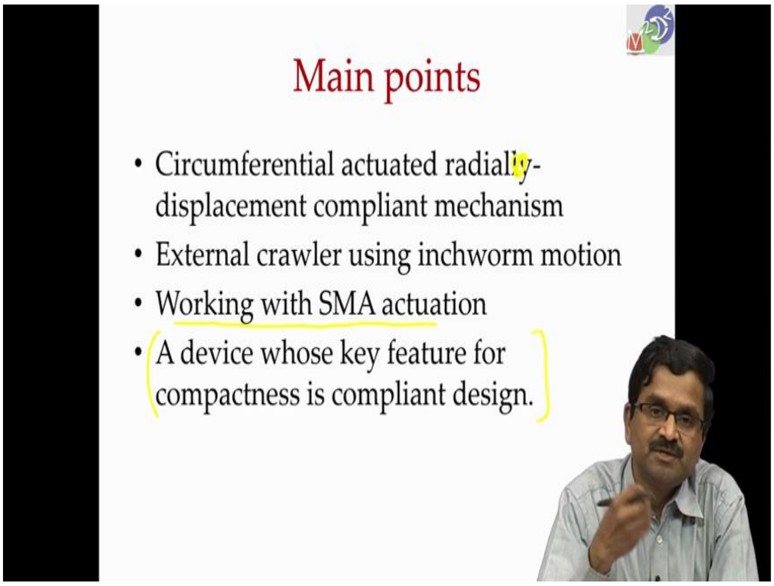

So, to recap to the main points here: we have used a circumferentially actuated, radial displacement compliant mechanism that is fully complained, that is something to remember we started with a rigid body linkage that have 24 joints and (Refer Time: 32:35) it into compliant that has no joints entire is single peace, it is a external crawler there are not too many external crawler in the literature. It moves on the outside without legs it is a gripping and moving so very compact and you also showed how were what should when we have SMA actuation, because we have to have a stiffness matching with SMA actuation, so that mechanism stiffness is in between the two extreme stiffness's of SMA its Martensite and Austenite phases, and we used compliant mechanisms in device that is reasonably sophisticated let say the robot, a device crawls in a pipe.

Thank you.