Robotics and Control: Theory and Practice
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Lecture – 36
Smart Needles for Percutaneous Interventions-II

Good morning, today we have the lecture on Smart Needles for Percutaneous Interventions specifically we are focusing on design 2. The smart needle design 2 and the control of a smart needle using slightly more control.

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The design 2 states that it has four degrees of freedom; the first degrees of freedom is the translation motion which is done by this rack and pinion system and then it has revolute joints which are realizable by the SMA wire actuators attached to the lateral side of the needling system. So, this is the cad model which shows the design 2 which we have developed in our lab and this is the reference of this work is given in this citation.

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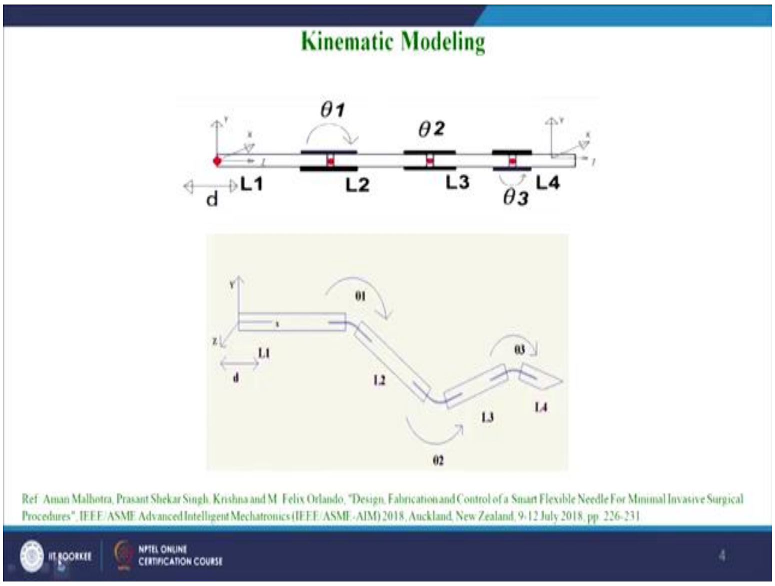

Now, coming to the kinematic modeling of the design 2 smart needle, it has four degrees of freedom. First being the translational degrees prismatic joint based. So, that the whole needle is pushed forward or pulled backward and the second degrees of freedom is a revolute joint which has 2 SMA wires attached on the lateral surface.

So, that this is the joint axis and similarly θ_2 which is the third degrees of freedom and the fourth degrees of freedom is also a revolute joint realizable by the attached the SMA actuators. This is the line diagram which shows how the degrees of freedom are actually happening and what we.

So, $\theta_1, \theta_2$are with the same plane whereas, θ_3 is 90 degree away from the planes of θ_1 and θ_2 and hence we have the D-H parameter α_3 coming out to be 90 here.

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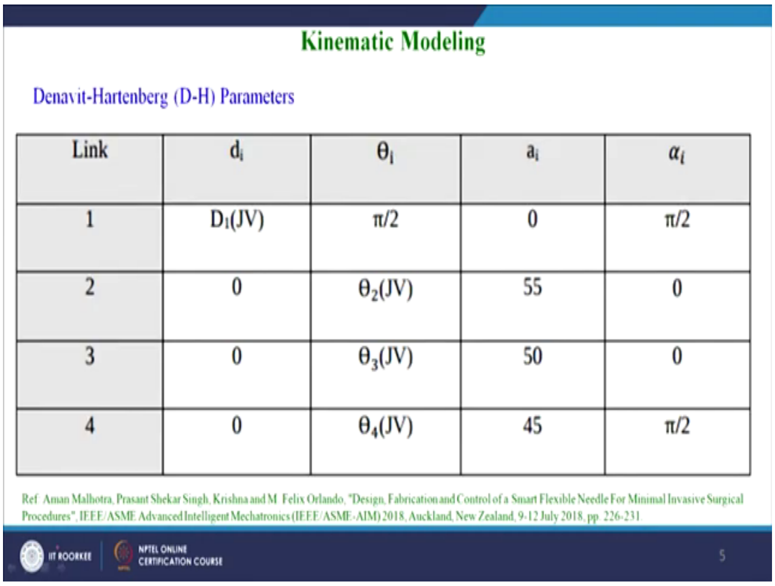
Kinematic Modeling

Denavit-Hartenberg (D-H) Parameters

Link	d_i	θ_i	a_i	α_i
1	D_1(JV)	π/2	0	π/2
2	0	θ_2(JV)	55	0
3	0	θ_3(JV)	50	0
4	0	θ_4(JV)	45	π/2

Ref: Aman Malhotra, Prasant Shekar Singh, Krishna and M. Felix Orlando, "Design, Fabrication and Control of a Smart Flexible Needle For Minimal Invasive Surgical Procedures", IEEE/ASME Advanced Intelligent Mechatronics (IEEE/ASME-AIM) 2018, Auckland, New Zealand, 9-12 July 2018, pp. 226-231

Now, coming to the D-H parameter dynamic Hardenberg parameters for the system developed is having the first joint variable D 1 and the second third and fourth joint variables being θ_2, θ_3 and θ_4 respectively. Where the link lengths what we have considered here for this robotic needle is 55 millimeters and 50 millimeters and 45 millimeters.

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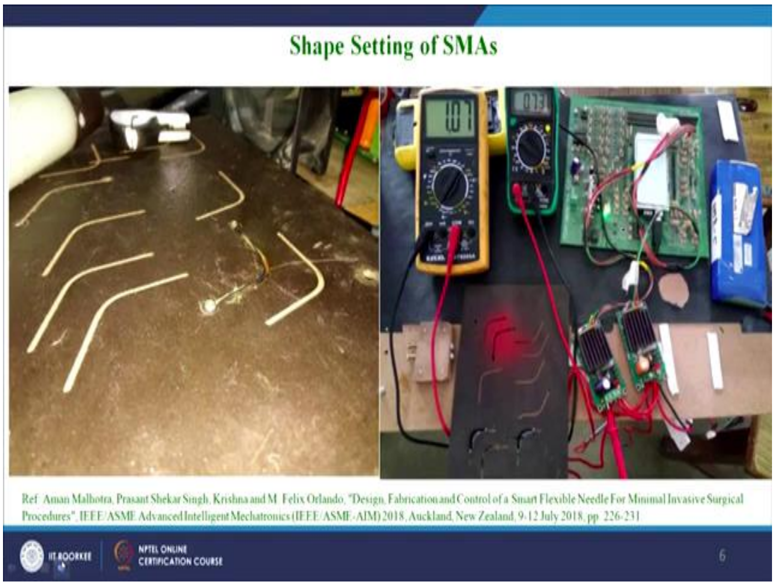

Now, coming to the shape setting of the SMA actuator wires. We have chosen the nitinol wire actuators, so that it gives more pulling power compared to the other forms of SMA actuator wires. So, we have first heat at the system to 90 degrees Celsius and we have given shape which is this shape.

So, that after cooling it can be deformed into any other shape and then by heating it, it will come back to its original state, which is the memory which it has due to the phase transformations that happens in the crystalline structure of this shape memory alloy wire. And of course, by passing current through it we could able to heat the wire and hence it can come back to its original shape.

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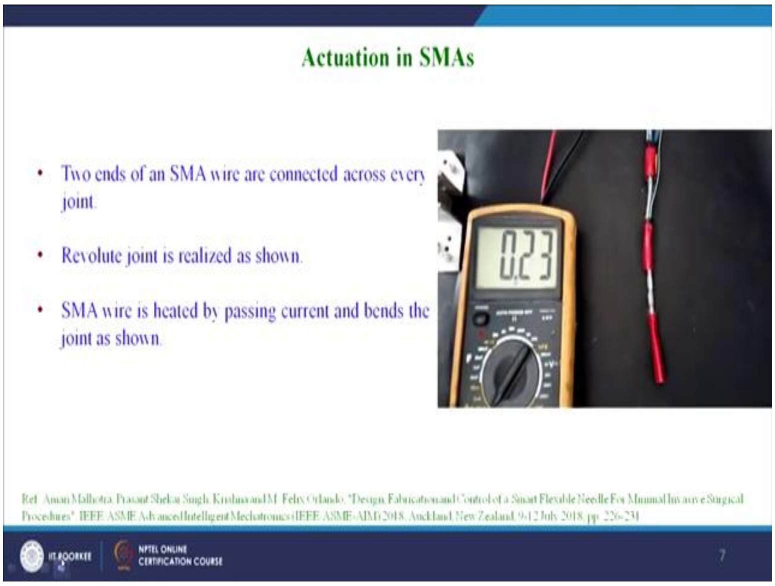

How the actuation is done for the needling system through the SMA wire is shown here. As you can see that by passing current through this lateral side SMA actuators we can have this bending degrees of freedom which is what is shown here is the revolute joint is realized by passing current through the lateral side SMA actuators.

Here the two ends of the SMA wire are connected across every joint to realize the degrees of freedom especially the revolute joints and the SMA wire is heated by passing the current and hence the joint is bending as shown in the schematic or in the video.

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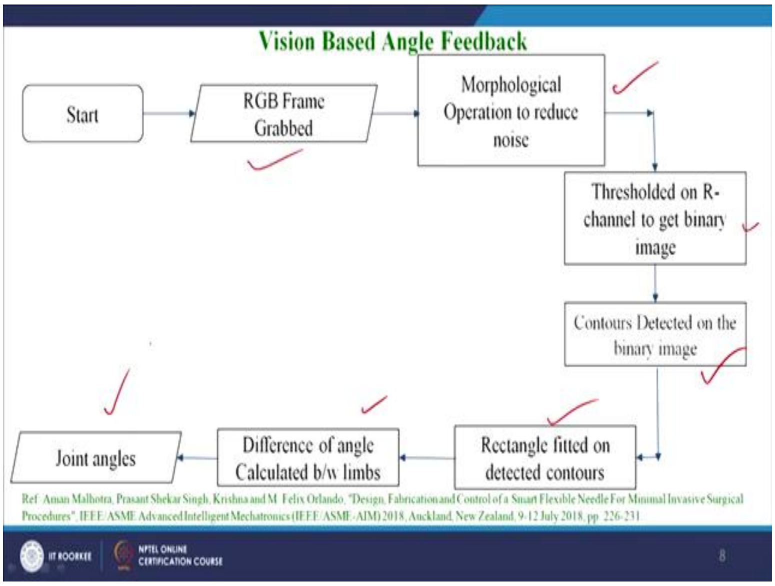

Now, coming to the vision based angular feedback. So, we have seen the bending of it and we want to grab that actual angle of the bending of the needling system by a vision camera system a vision system; which is here stereo camera system to get the bending angle of the robotic smart needle.

So, we just started we grabbed the RGB figure that is a frame through the video and morphological operation is done to reduce noise, then thresholding is done after the morphological operation. Thresholding is done to get the binary image, then contours are detected on the binary image. The contours are not in a regular shape, so to make it regular we just fixed or fitted rectangular shapes on the contours detected contours. Then the rectangular shapes the angle between the successive rectangular shapes give the joint angle for the developed smart needle.

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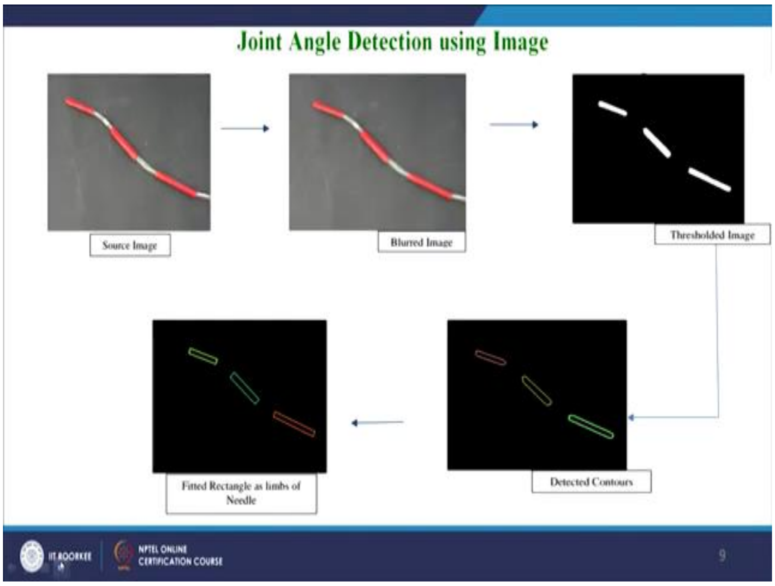

Precisely this is what happening; first the source image which is the RGB then we blurred it then we get the threshold image, which is basically a binary image then we detected the contours which is not exactly rectangular in shape. So, we made it rectangle by fixing a rectangular shape on the contours successive contours, then we got the joint angles between the successive. So, this way we can find the joint angles this is θ_2, this is θ_3, this is θ_4.

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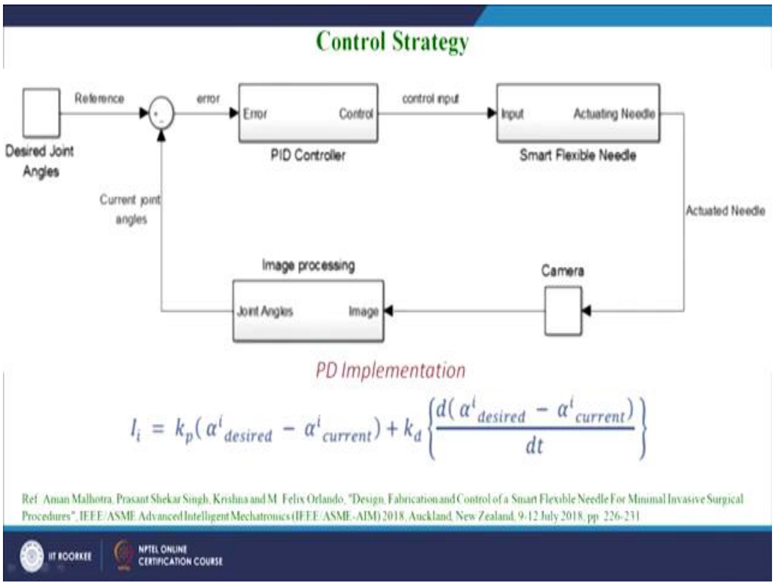

And now coming to the control strategy; the control strategy is such that given the desired angle. So, what is the basic objective of this needling system is that the whole shape of the needle should go and get set with the desired shape given. Suppose this is the shape to reach this target inside the cancerous region. So, we aimed with this objective such that we targeted this objective in such a way that this could be the obstacle and this could be the obstacle, but we need to reach this target by a smart needle.

So, we did not even like we not only focused the tip we have focused the shape of the needle also that is why our target is our aim is to have the desired joint angles to be matched by the robotic needle system. So, that our aim is given the desired joint angles to reach this target our robotic needle should also go and get set in this fashion.

So, distance like this difference between this angle and this angle and this angle must be minimized that is that difference is the error that is getting minimized by the control strategy, which is a PD control, PID control strategy is used basically it is a PD controller.

And it is such a way that desired joint angle we provided the desired joint angle and we have the comparator such that the error comes that is fed to the PID controller and then the control input is fed to the power amplifier part of the actuating needle smart needle and hence the needle is bent. And that bending of the needle is captured by the feedback system which is the vision feedback system camera from that the imaging analysis is done to get the joint angle between the rectangular contours that is denoting the links the joint angle between the flexible links of the needle that is fed back as actual joint angle of the needle.

And then this algorithm or the control strategies continued till we reach the final destination. The controller precisely that is going to the needle is the current which is given by this expression which is

$$I_i = k_p\left(\alpha^i_{desired} - \alpha^i_{current}\right) + k_d\left\{\frac{d(\alpha^i_{desired} - \alpha^i_{current}}{dt}\right\}.$$

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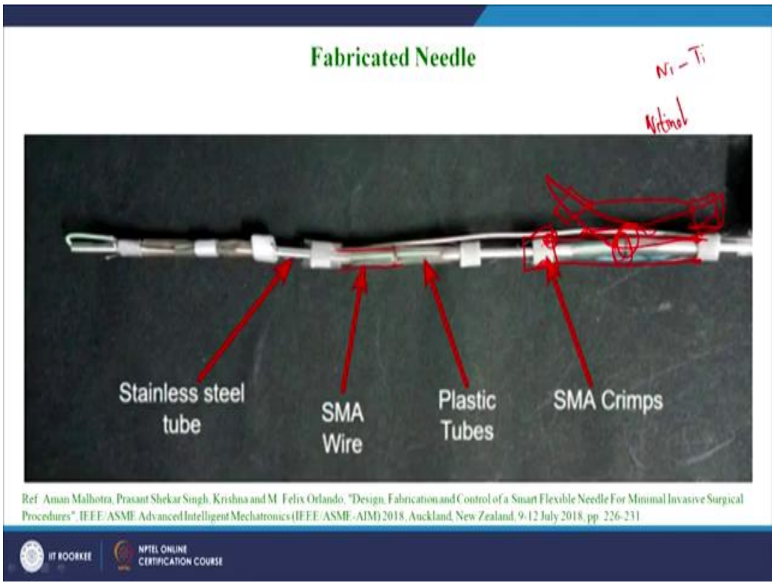

Now, this is the fabricated needle which we have developed. So, as to have a smart actuation, so that the target is reached with the contour shape over the needling shape of the path.

So, this is the one where we have this stainless steel tube body where the SMA wires are attached here in the lateral surface of the needle and plastic tubes are covering it. So, as to have the safe operation when this needle is inserted inside the conducting region like tissue region or phantom tissue region and these are the crimps; SMA crimps these are meant to have the SMAs fixed to it. So, that once the current is pass through it this SMA wire gets contracted to its original shape.

So, during that time this crimp is the one that keeps the SMA wire getting attached to it; it would not release the SMA wire. So, what happens here is this joint is realized in such a way that this system because of that contraction the system behaves like this. So, here due to the contraction of this is a crimp here is a crimp now.

So, due to the contraction of this SMA wire attached on the lateral surface of the needle we have the needle getting bent on around this joint or at this joint. So, this is the actuation with the SMA actuator wire; the SMA actuator wire is the nitinol wire which we have used ok. So, it is basically the combination of nickel; nickel and titanium combination.

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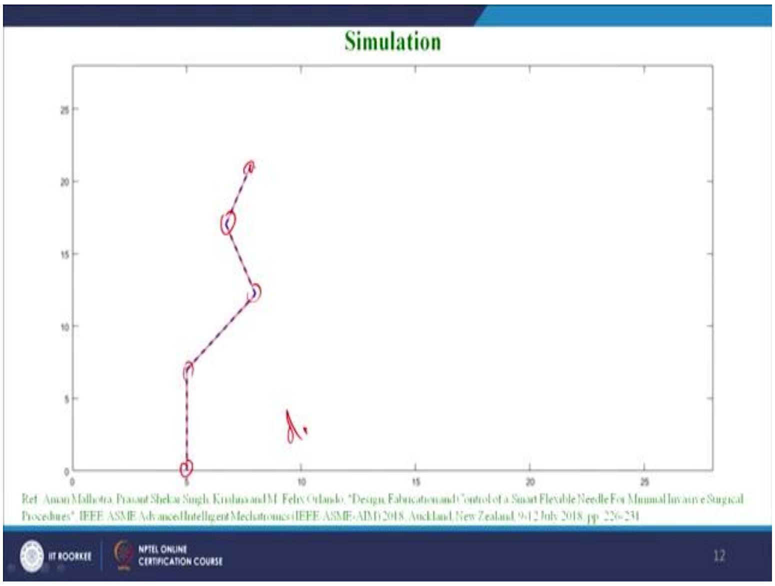

And this is the simulation where you have the blue wire, blue line is the desired joint angular shape of the needle while reaching this target and the red one is the needle actual needle coming and following that you can see it again that it is a insertion part and the needle is coming and getting set with this joint angles first, second and third. It is getting pushed by the first degrees of freedom which is the prismatic joint degrees of freedom d_1. As you can see here comes getting set for the second joint first joint angle, second joint angle and third joint angle and finally, it gets into the shape of that desired trajectory.

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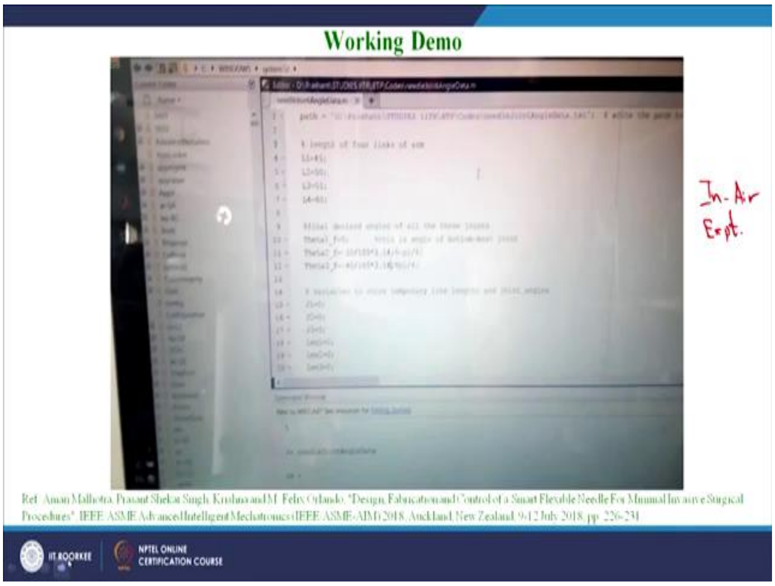

And this is the working demo which shows that the needle has been designed kinematically it has been modeled kinematically using the robotic principles through MATLAB m file programming and we have simulated also then it has been experimentally shown the working demo. And that is basically what we have done is in air experiment with the needling system. So, this is the video which is shown here. So, these are the links of the needle and the simulation is achieved with the MATLAB m file coding.

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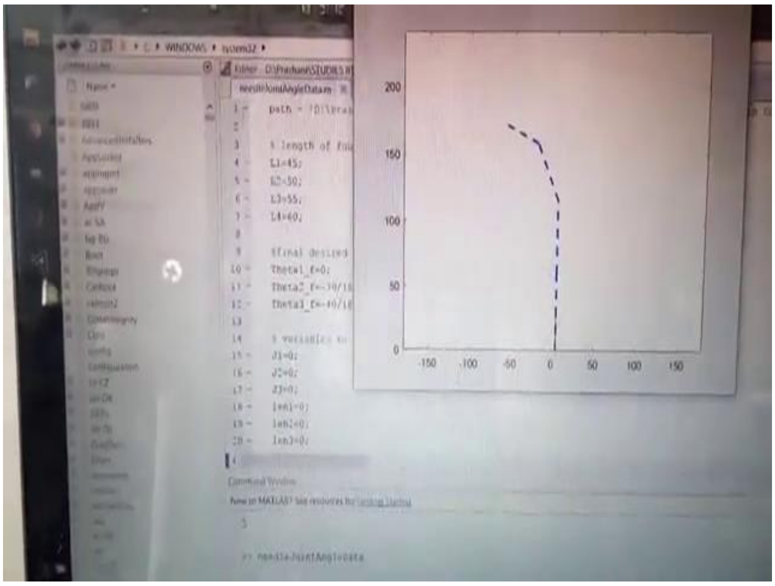

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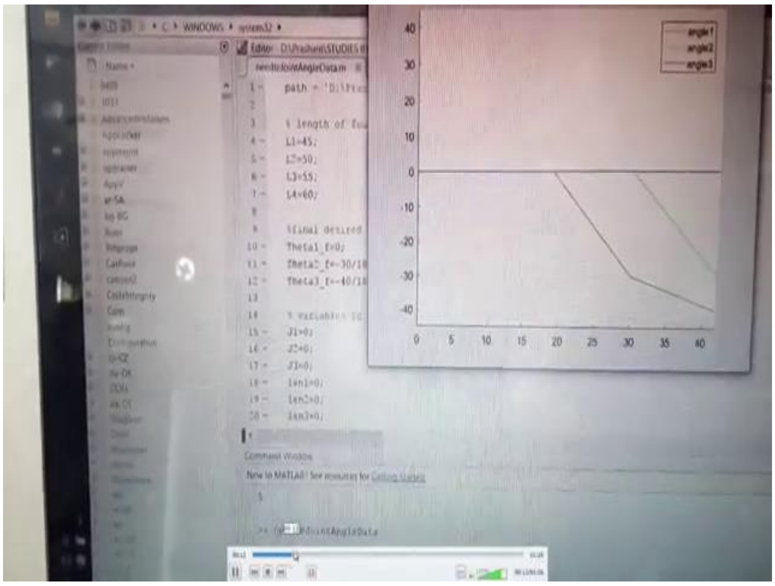

Then we can just take it forward to precisely see that contours are getting formed.

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And here is the experimental setup where in the top we have attached the vision system vertically mounted to capture the top view of this system. So, you can see that the rack and pinion system here is pushing the needle forward and the SMA actuators are getting the current and due to which it is getting a contracted it gets contract and the bending of the needle is happening here. So, that the curved trajectory can be traced by the needling system.

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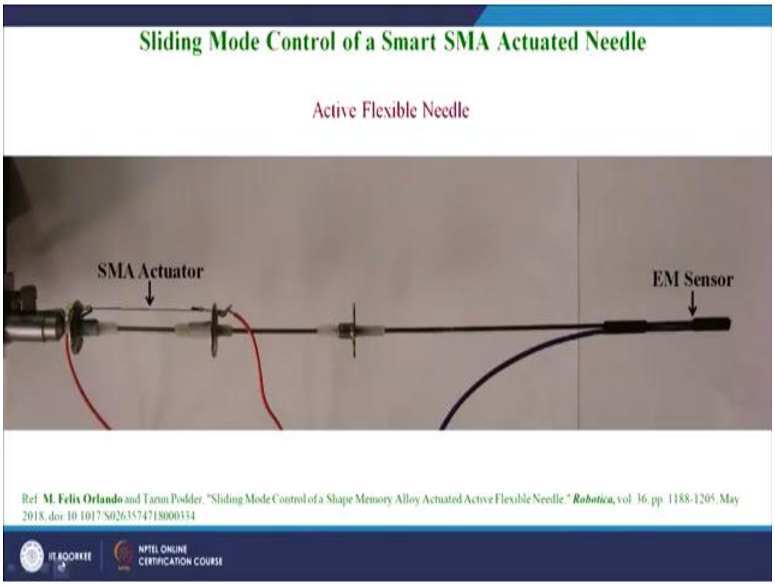

So, now coming to the robust control of a smart SMA actuated needle. So, this one we have done in order to see that the disturbance given to it can be overcome or not. Because of once the needle is inserted into the real tissue there could be lot of disturbances coming to the needle and how the needle is going to face that and overcome those disturbances.

So, to avoid to have the robustness of their needle control strategy we have considered sliding more contour of a smart SMA actuated needle designed by us. So, this is the active flexible needle, where the reference is given in this paper the citation of this work is here shown here which is by myself and professor Tarun Podder. And here is the needling system which is developed by professor Hutapea from Temple University, he is our research collaborator. And here is this needling system which is made up of aluminum body which is of length 200 millimeter and we have the discs to connect the SMA actuators.

The SMA actuator is of length 70 millimeter and 0.35 mm diameter and you can see that it is attached to the disc through the crimps. So, that the crimps will do the attaching firmly to the discs or the ends of the SMA wire actuator and you can see that the EM sensor; Electromagnetic sensor is attached to the needle tip. So, as to track the needle trip; needle tip with good accuracy.

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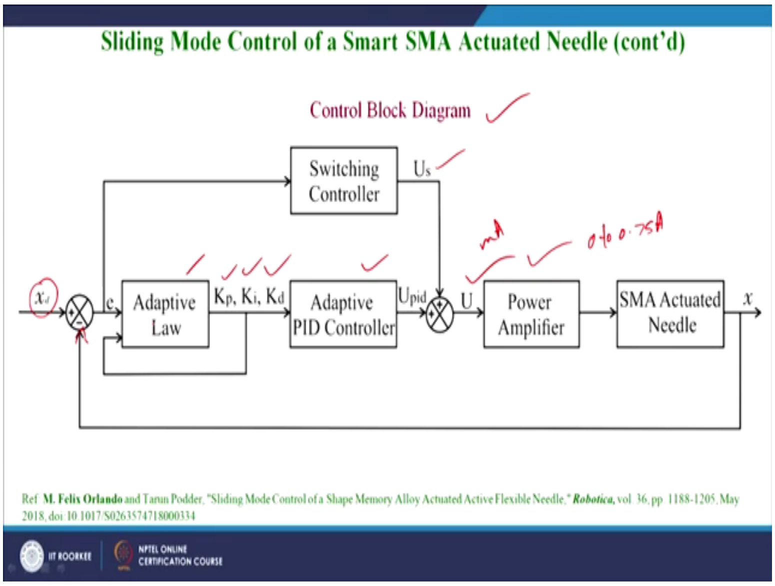

Now, coming to the sliding mode control strategy of this smart needle. So, the block diagram is shown here where x_d is the desired position for the needle or the desired trajectory and we have the first block is the adaptive law to update the K_p, K_i, and K_d getting tuned through adaptive law. And the controller is the summation of switching controller and the equivalent controller which is $U_s + U_{pid}$ and that control signal is fed to the needle through the power amplifier, because the current to the needle before the power amplifier is in milliampere.

So, that must be given or amplified to ampere range. So, the range that is given to this needle is 0 to 0.75 ampere and then the needle is bent. That deflection of the needle is captured by this EM sensor attached to its needle tip to the tip of the needle that gives the actual position of the needle tip or the actual deflection of the needle tip that is fed back here to get the arrow signal and this procedure continues till the last target is reached.

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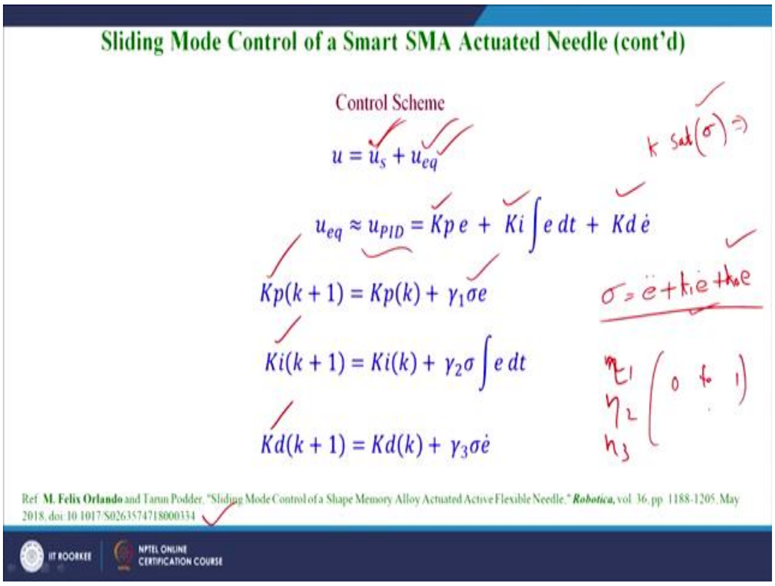

So, the sliding mode controller is having the two parts; first part the second part. Where the first part is the discontinuous part which is given by $ksat(\sigma)$, where σ is the sliding surface which is given by $\sigma = \ddot{e} + k_1\dot{e} + k_0 e$. So, this is the sliding surface which we have considered in our study and how and why this has been taken has been given in this reference clearly.

So, the discontinuous controller is given by this equation which is in such a way that it brings the actual trajectory of the system to be lying on the sliding surface. And equivalent controller is taking the form which is given by $u_{PID} = k_p e + k_i \int e\,dt + k_d \dot{e}$.

Where the update laws for the k_p, k_i and the k_d gains proportional derivative and the integral gains are done by steepest gradient steepest algorithm which is given by $k_p(k+) = k_p(k) + \gamma_1 \sigma e,$ where σ is the sliding surface given by this equation. And then we have this equation having the learning rates η_1, η_2, and η_3 for the respective gains which is taken between 0 to 1.

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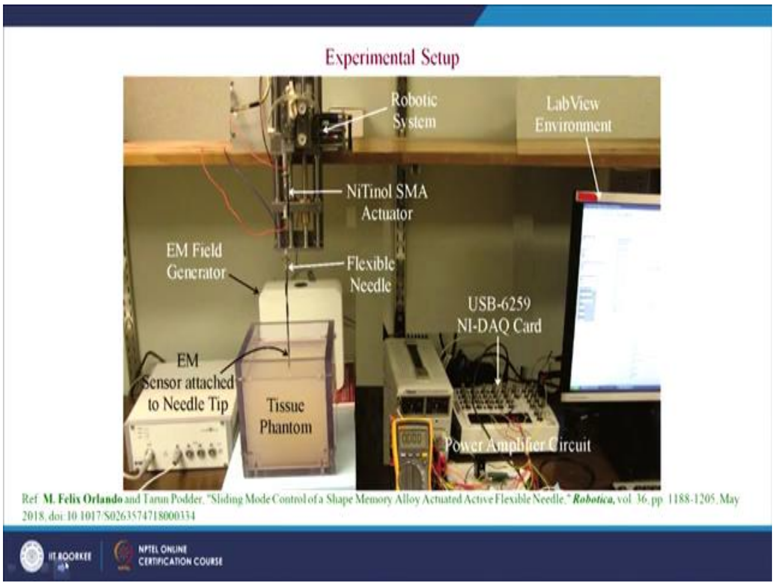

Now, coming to the experimental set up. The experimental set up is the one where we can see the sensory system EM tracking system and the EM sensor attached to the needle tip. And the tissue phantom is shown here which is an artificial tissue and here is the robotic system where the needle base is attached and here is the actuator which is the nitinol SMA actuator. And we have the interface by USB 6259 NI DAQ card interface and the power amplifier circuit is to amplify the input current to the range of 0 to 0.75 ampere and the working platform is lab view real time platform.

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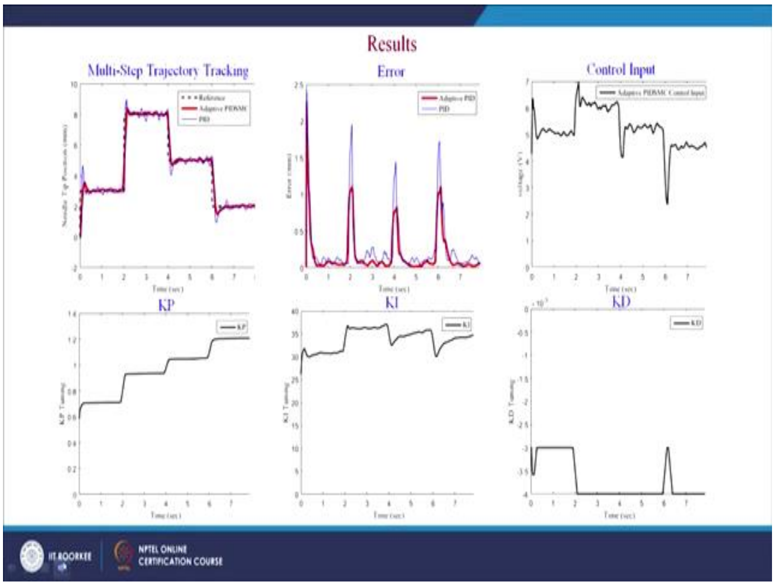

Now, coming to the results associated with this work we have performed the analysis through multi step trajectory tracking. First we have given the multi step trajectory, we have first given started with 4, 3 millimeter, then we started with 8 millimeter, then we have given another random step then again a random step.

So, then we have traced that trajectory given desired multi step trajectory with both PID control strategy as well as the adaptive PID sliding mode control strategy which is the one we have used in our model in order to have the robustness and also have the to have the finite time convergence. And we can see that the error corresponding to each multi step is shown here where the PID error is significantly greater compared to that of the adaptive PID control strategy.

Then this is the control input accordingly varying between 0 to 7 volt for each multi step, and then we have the ranges of the tuning of the K_p, K_i and K_d as shown here which varies between these ranges 0 to 1.44 K_p and 0 to 44. That is 25 to 44 K_i and K_d is having in terms of 10 power minus 3 range and now we have also tested with sinusoidal trajectory giving.

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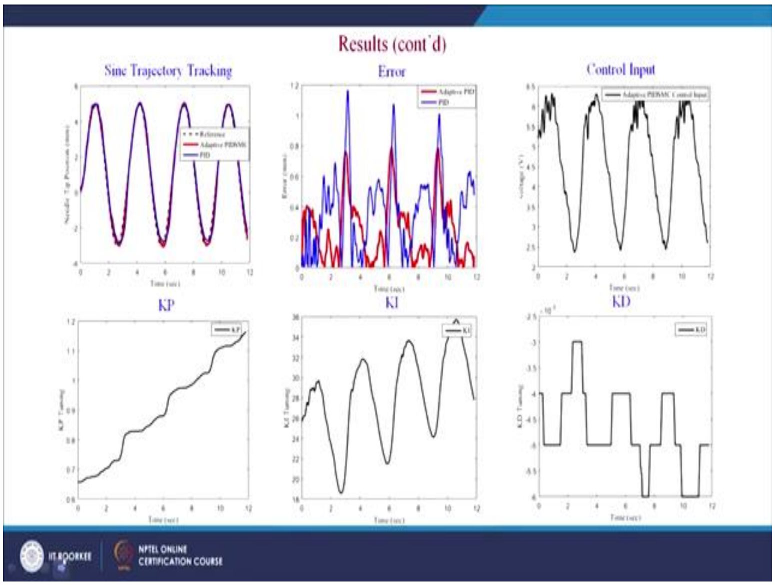

So, we have given the sinusoidal trajectory. So, that the needle can take the continuous trajectory as shown here and the error for that is given in this figure 2, where the control input is shown in figure 3. And corresponding K_p tuning value K_p, K_i tuned value and K_d are shown in this figures which are varying between 0.6 to 1.24 K_p and 8 into 36 for K_i and it is varying in the range of 10 power minus 3 for K_d.

Both the situations we have observed that K_d is almost less value why because we are highly interested in having the very small moment we do not want very quick response for the system because we are going to insert this needle inside the flesh tissue. So, that the needle insertion should not be harming the healthy tissue. So, that it can track the trajectory rather it should not disturb the healthy tissue around that trajectory and or in the neighborhood of the trajectory.

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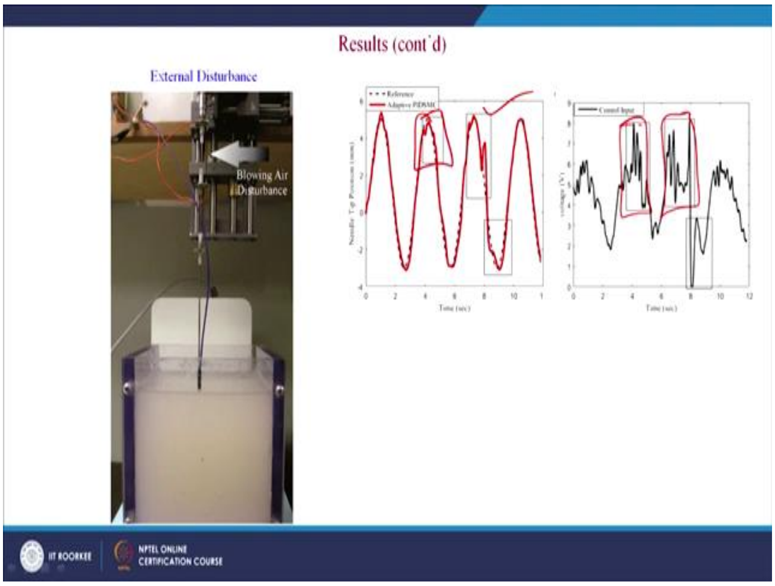

That is why what we have observed is we have seen that the trajectory that K_p value in both K_d value in both the situation for both tracking the multi step trajectory as well as the sinusoidal trajectory is less compared to the K_i and K_p values.

Now, coming to the disturbance like we have we want to test the robustness of this control strategy in this application. So, we have given the first disturbance in terms of cooling the heated SMA actuator wire. So, that what we have done is we have blown air and that could be the disturbance. During the tracking of the sinusoidal trajectory at certain instance we have blown the cooling air to the heated or continuously heating SMA actuator and we have observed the response as in the trajectory tracking. And this is the corresponding control input variation during the disturbed period and the response is much better.

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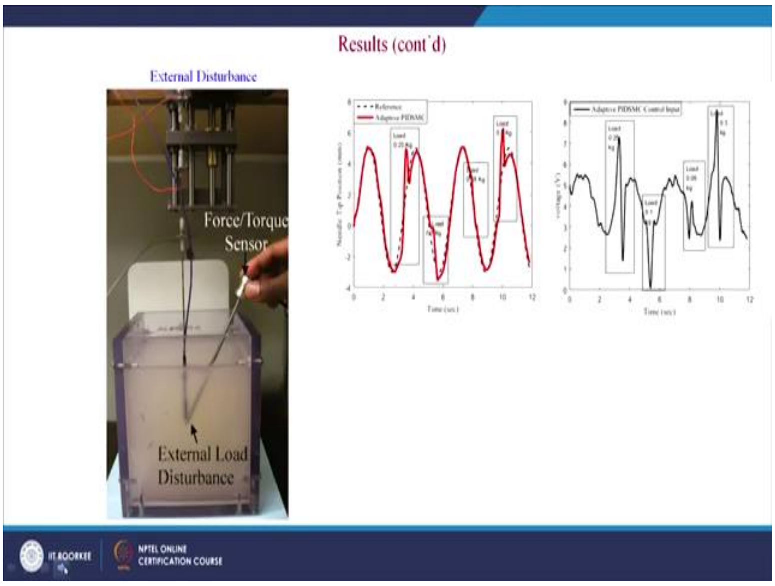

And now we have given one more disturbance which is in terms of external load disturbance that is the tip of the load, the tip of the needle is disturbed by the force torque sensor by giving 0.25 kilogram, 0.1 kilogram, 0.01 kilogram, 0.3 kilogram. The 0 to 0.5 kilogram range we have given the disturbance at the needle tip while traversing or while traveling the our tracking the desired trajectory say sinusoidal trajectory it has to go here come back go here come back that is the sinusoidal trajectory for this needle tip.

During that time we have disturbed the needle tip by this particular ranges of force, then we have observed the response of this adaptive PID sliding more controller where this perturb perturbance or the disturbance it has during the tracking is much better compared to that of the PID controller. This is the response of what we have observed.

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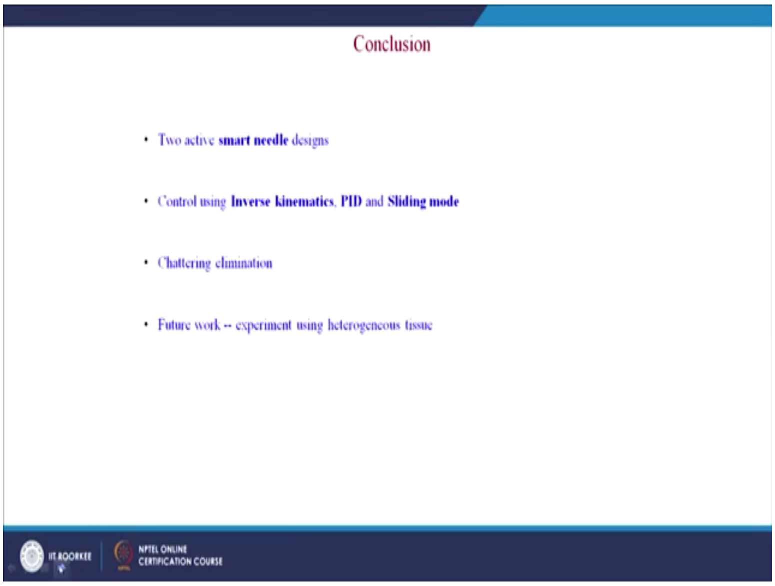

And coming to the conclusion, we have seen in this lecture to active needle designs and then we have performed controller using; we have performed the control of the design needles using inverse kinematics control strategy that is CLIK and the other one is PID controller and then the robust sliding mode controller.

Then next or the future step for us is to avoid the chattering during the control strategy for this needle application in the percutaneous interventions. And we will be performing that using the hetero heterogeneous real tissue biological tissue that is our goal.

Thank you so much.