Robotics and Control: Theory and Practice
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Lecture – 35
Smart Needles for Percutaneous Interventions-I

Today we are going to see about the Smart Needles for Percutaneous Cancerous Interventions. The outline of this lecture will be on introduction then design 1 of the smart needle and the design 2 of the smart needle coming to the conclusions.

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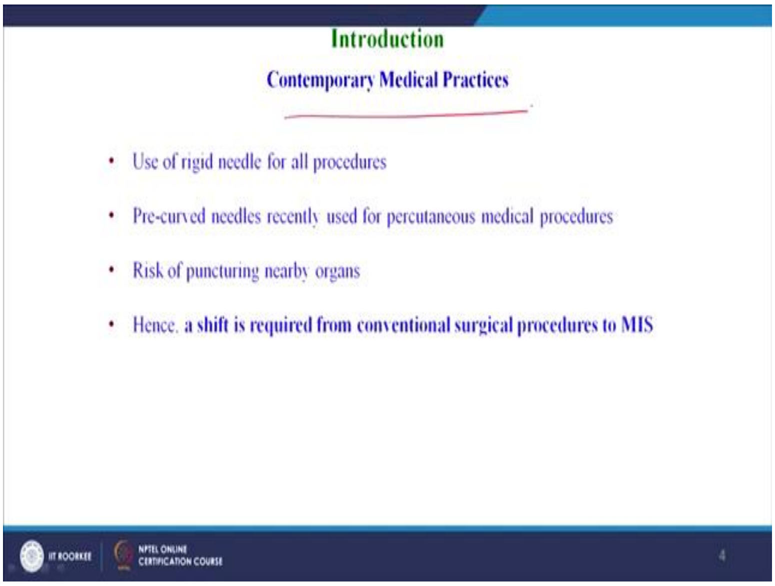

Coming to the introduction, first we see in the contemporary medical practices the use rigid needles for all the surgical procedures. Sometimes recently pre-curved needles are used for percutaneous medical procedures and the rigid needles usage will lead to risk of puncturing the nearby healthy organs when they target a specific region.

Hence a shift is needed from conventional surgical procedures to minimal invasive surgeries.

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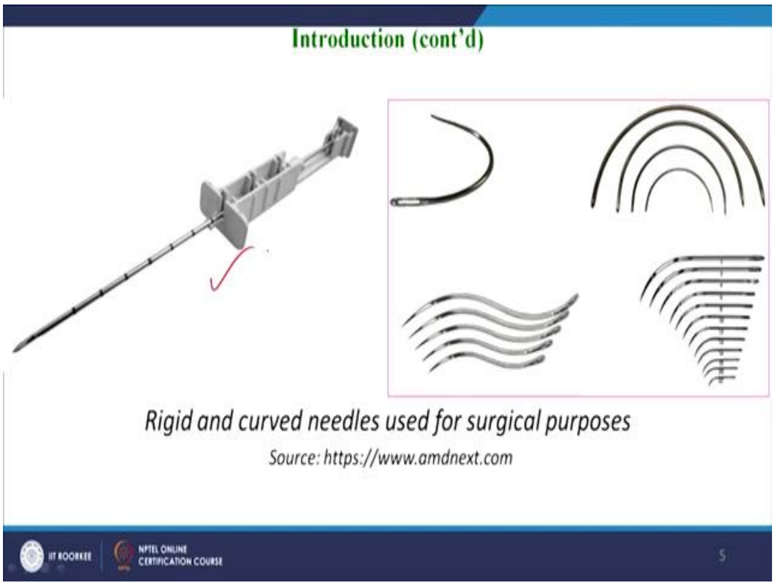

The conventionally used rigid and curved needles are shown here in the schematic which is the rigid needle, but it has the flexible nature as well to some extent it is quite flexible also and the pre-curved or the curved needle is shown here. So, rigid structure with the curved shape and this source is taken from amdnext.com.

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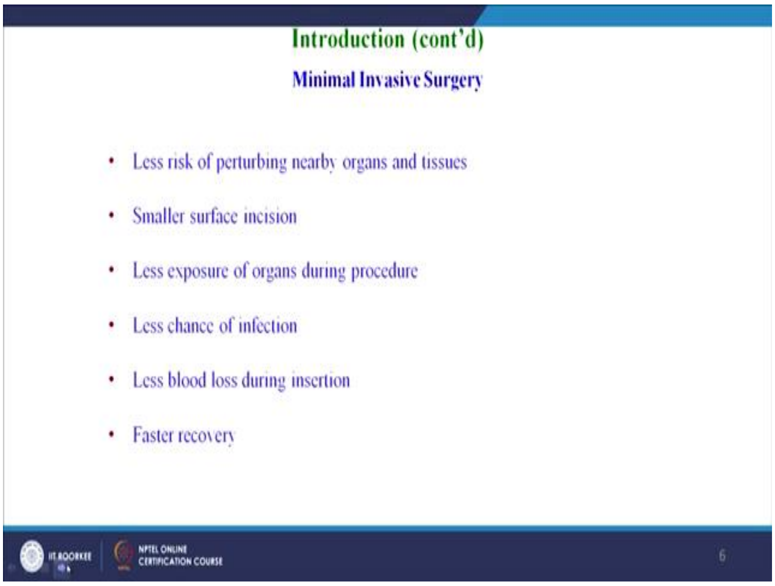

Now, coming to the minimal invasive surgery; the advantages of minimal invasive surgeries as you can see that less chance of infection and less blood flow or blood loss during the insertion and there is a recovery chances very fast there and smaller surface incision and less risk of disturbing the nearby organs or the healthy organs on the tissues and less exposure of organs during the procedures such as brachytherapy and biopsy.

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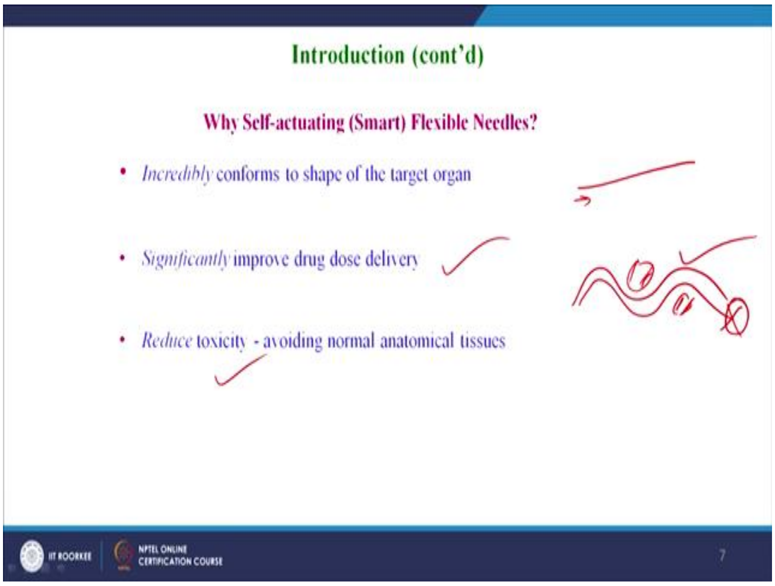

Why self-actuating or why smart needles? Smart needles are what they have the self-actuating capability this is a rigid needle this needle is pushed at the base.

So, that the tip can go forward whereas, a self-actuating or the smart needle will have the self itself getting bent. So, as to avoid anatomical obstacles to reach the target region and it significantly improve drug dose delivery during the procedure and it reduces toxicity usage of smart needle will reduce toxicity thereby avoiding anatomical normal tissues or the healthy organs nearby.

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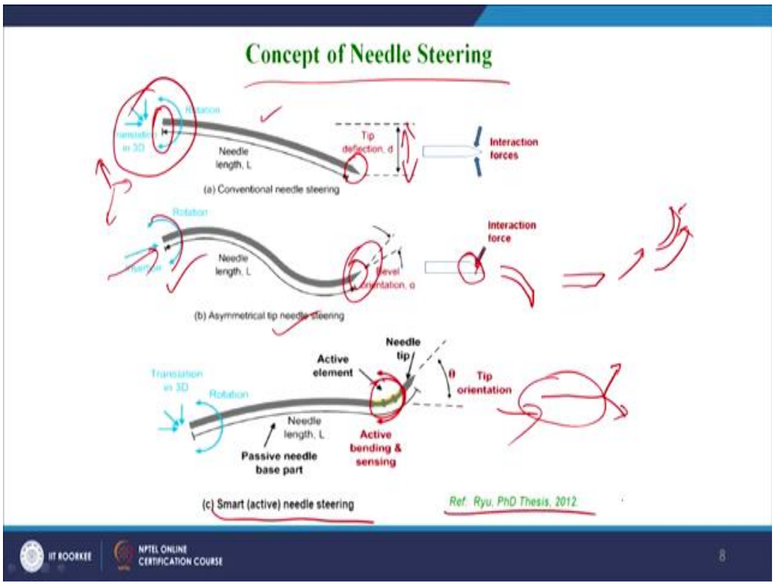

The concept of needle steering coming to the concept of needle steering conventionally the needles are getting steered or maneuvered and manipulated in such a way that they are manipulated at that base by translation, which is in 3D both all together in x y and z axis translation happens and it has been also rotated at the base. So, that a small variation at the base leads to heavier or more deflection at the tip of the needle with a rigid needle and it has the shape of the needle tip being conical that is symmetric needle tip.

So, that the reaction forces to the needle tip is shown here both the sides equal reaction force and asymmetric tip needle steering that is needle has the asymmetric tip. So, that it is having a bevel shaped needle tip where the bevel angle is generally varied from 30 degrees to 60 to 65 degrees. This is having the needle steering at the base insertion and rotation around the needle axis.

So, two inputs are given; input 1 insertion input 2 rotations to move forward, but the reaction force on the tip is such that the bevel surface is having reaction force from the tissue. So, that it takes the shape because of the reaction force. When you spin it and you make it, it becomes like this so that the reaction force will lead to this type of shape of the needle.

So, the shape the needle because of its bevel tip depends on the tissue reaction force to take its configuration or curvature. The smart needle active needle concept is such that it will have a it will have an active element attached to the needle tip or close to the tip or the tip region so that this active element being actuated will bend this tip this side or this side. So, that the whole body of the needle follows it, the whole body being flexible will follow the needle tip by pushing at the base of this needle. This concept we have observed or learnt is from Ryu in his PhD Thesis 2012.

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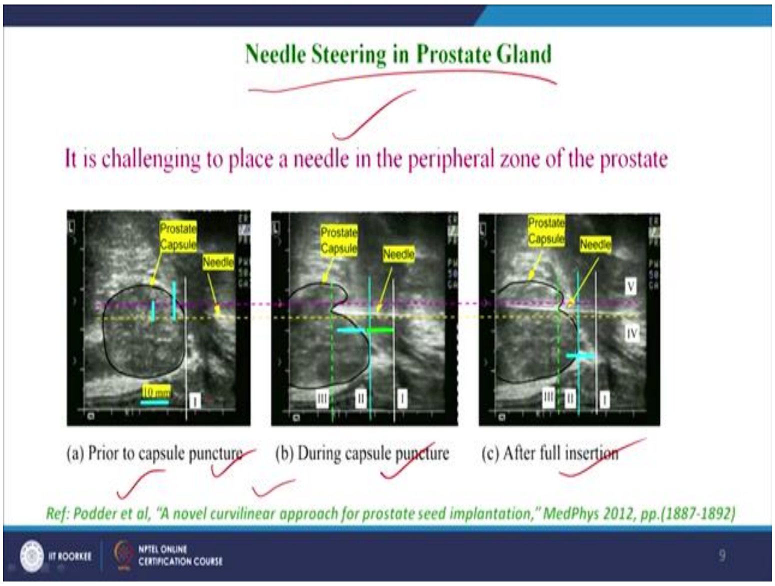

So, now coming to little deeper needle steering in prostate gland, this is the extensive study performed by Prof. Tarun Podder from his reference from his research article which is entitled as A novel curvilinear approach for prostate seed implantation, in the medical physics journal in 2012 they have observed that it is quite challenging to place here conventional rigid needle in the peripheral zone of the prostate gland.

As you can see the video snapshot here 1, 2 and 3, in the phase 1 the needle is approaching here to insert the prostate capsule phase 2 here is it is penetrating the prostate gland and the gland the prostate capsule is also getting deformed by the rigid needle insertion and after the insertion it comes back to the normal shape of the prostate capsule and you can see the needle getting inserted and going to the periphery of that prostate gland.

So, you can see the prior to the capsule puncturing during capture capsule puncturing and after full insertion into the capsule of the prostate. So, what we seen is to reach the periphery of the needle the other organs of the prostate may also be getting inserted or damaged or getting penetrated by the needle.

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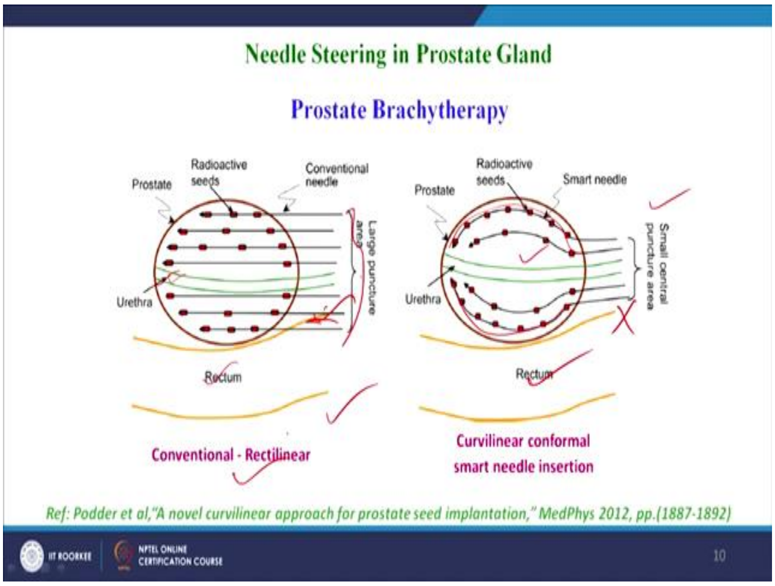

Thus the schematic shows here more clearly that conventional rectilinear approach uses rigid needles, but the radioactive seeds attach to it penetrated into the prostate gland where it is the radioactive seed or the radioactivity is getting exposed to the healthy organs rectum and urethra. Urethra is the green line shown here and the rectum is with the orange line show in that rectum region and the urethra region here.

The conventional needles with the radioactive seeds are penetrated in order to go to the periphery of the prostate gland whereas, the concept by professor Tarun Podder it is observed that with the recti with the conventional curvilinear with the proposed curvilinear approach the needles conform to the shape of the prostate gland you can see that its inserted and getting closer to the periphery of the prostate similarly in the down side also without affecting the neighboring organs urethra and the rectum.

There is no penetration here whereas, there is a penetration here by the needles into the rectum region and also close to the urethra and also you see that the puncturing area is more in the case of conventional rectilinear approach whereas, the as the approach proposed here by professor Podder is having smaller region and less number of needles getting penetrated into the prostate with the more exposure to the periphery of the prostate gland.

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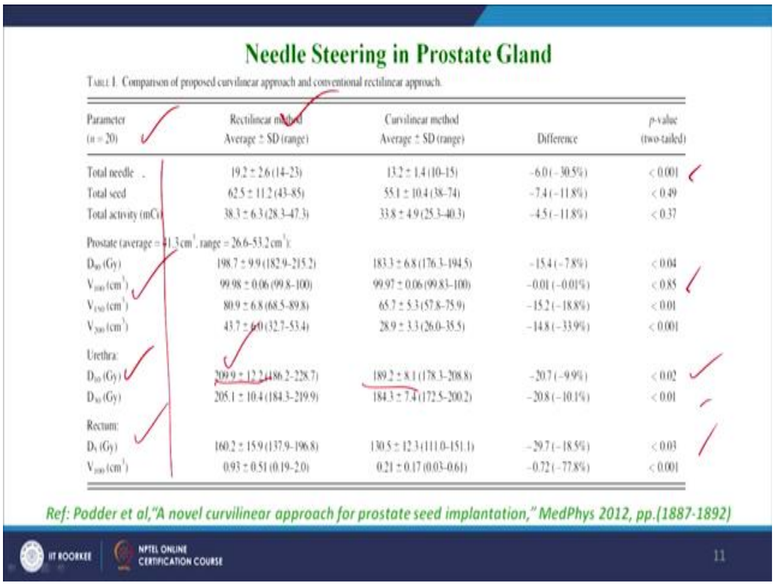

Needle Steering in Prostate Gland

TABLE I. Comparison of proposed curvilinear approach and conventional rectilinear approach.

Parameter ($n = 20$)	Rectilinear method Average ± SD (range)	Curvilinear method Average ± SD (range)	Difference	p-value (two-tailed)
Total needle	19.2 ± 2.6 (14–23)	13.2 ± 1.4 (10–15)	−6.0 (−30.5%)	< 0.001
Total seed	62.5 ± 11.2 (43–85)	55.1 ± 10.4 (38–74)	−7.4 (−11.8%)	< 0.49
Total activity (mCi)	38.3 ± 6.3 (28.3–47.3)	33.8 ± 4.9 (25.3–40.3)	−4.5 (−11.8%)	< 0.37
Prostate (average = 41.3 cm^3, range = 26.6–53.2 cm^3):				
D_{90} (Gy)	198.7 ± 9.9 (182.9–215.2)	183.3 ± 6.8 (176.3–194.5)	−15.4 (−7.8%)	< 0.04
V_{100} (cm^3)	99.98 ± 0.06 (99.8–100)	99.97 ± 0.06 (99.83–100)	−0.01 (−0.01%)	< 0.85
V_{150} (cm^3)	80.9 ± 6.8 (68.5–89.8)	65.7 ± 5.3 (57.8–75.9)	−15.2 (−18.8%)	< 0.01
V_{200} (cm^3)	43.7 ± 6.0 (32.7–53.4)	28.9 ± 3.3 (26.0–35.5)	−14.8 (−33.9%)	< 0.001
Urethra:				
D_{10} (Gy)	209.9 ± 12.2 (186.2–228.7)	189.2 ± 8.1 (178.3–208.8)	−20.7 (−9.9%)	< 0.02
D_{30} (Gy)	205.1 ± 10.4 (184.3–219.9)	184.3 ± 7.4 (172.5–200.2)	−20.8 (−10.1%)	< 0.01
Rectum:				
D_5 (Gy)	160.2 ± 15.9 (137.9–196.8)	130.5 ± 12.3 (111.0–151.1)	−29.7 (−18.5%)	< 0.03
V_{100} (cm^3)	0.93 ± 0.51 (0.19–2.0)	0.21 ± 0.17 (0.03–0.61)	−0.72 (−77.8%)	< 0.001

Ref: Podder et al,"A novel curvilinear approach for prostate seed implantation," MedPhys 2012, pp.(1887-1892)

So, this work has been compared with several patients and they have shown that conventional rectilinear approach has more dosage exposure to the organs. Main organ, target organ, prostate, urethra and the rectum being more compared to that of the you can see that exposure is more to dose exposure is more in case of rectilinear whereas, it is lesser significantly they are differing. The variation is significant compared to this two approaches with these number of parameters total seed total needle and total activity and the exposures are all significantly lesser in the proposed to curvilinear approach compared to the rectilinear methodology.

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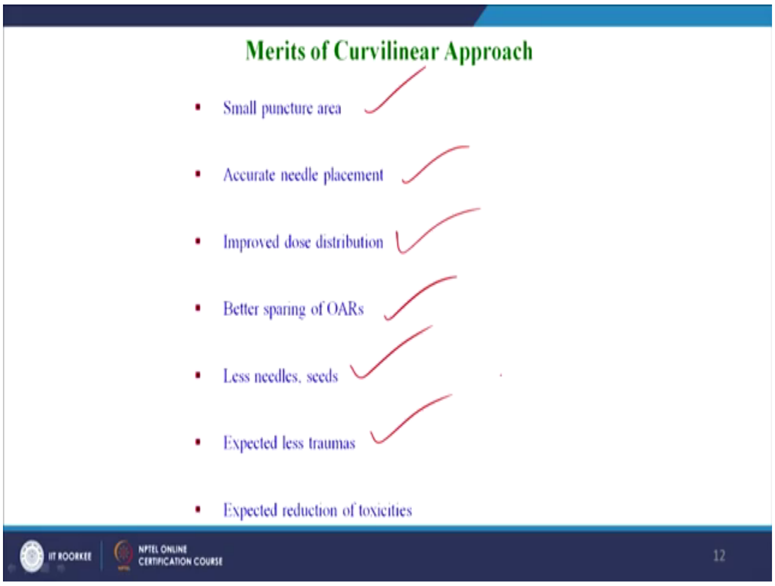

So, the merits of the curvilinear approach over the conventional one smaller puncturing area, accurate needle placement, improved dose distribution, better sparing of objects at risk such as rectum and the urethra and less needles; obviously, less seeds as well and expected less traumas and the expected less toxicities to the organs.

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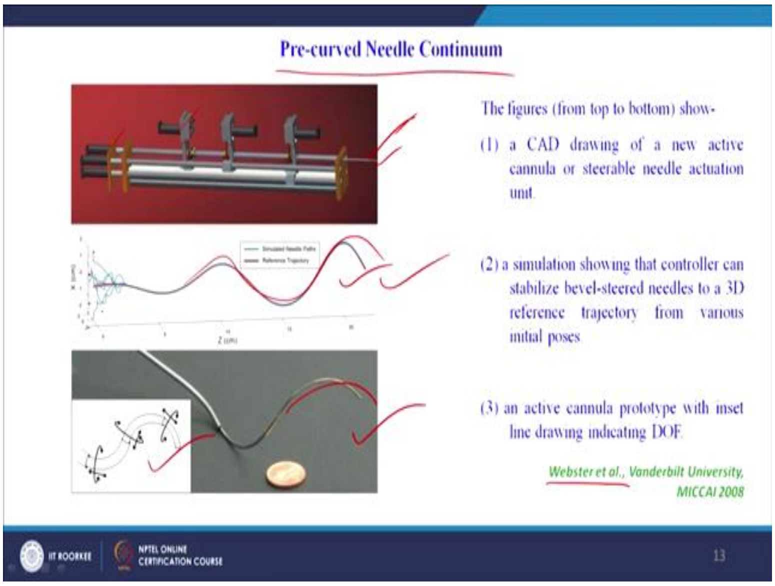

Now, coming to the state of the art concepts of the smart needles, the finest concept or the first concept is proposed by Webster et al professor Webster et al from Vanderbilt University. So, this is pre-curved needle continuum concept. So, the first figure shows the cad model of the system developed by Prof. Webster and figure 2 shows the simulation results while the target 3D trajectory has been traced by the needle more precisely and accurately. Similarly, the figure 3 shows the prototype of the active cannula with the schematic shown here in the inset line drawing indicating the degrees of freedom.

So, this system has 6 degrees of freedom it has 3 concentric tubes and it has 6 degrees of freedom for 1 concentric tube there is 2 motor there are 2 motors, 1 for translating forward or bringing it backward moving in the translation direction and one more motor is for the rotation of that or spinning of that tube.

So, that it each tube is a super elastic material tube. So, that once the getting actuated they will get the shape accordingly and to have the different shape because of that elastic property we will get confirmed by the actuation we will make it get confirmed with the desired shape or the reference trajectory given there that is why if you start from any initial positions you can get merged with the desired trajectory given.

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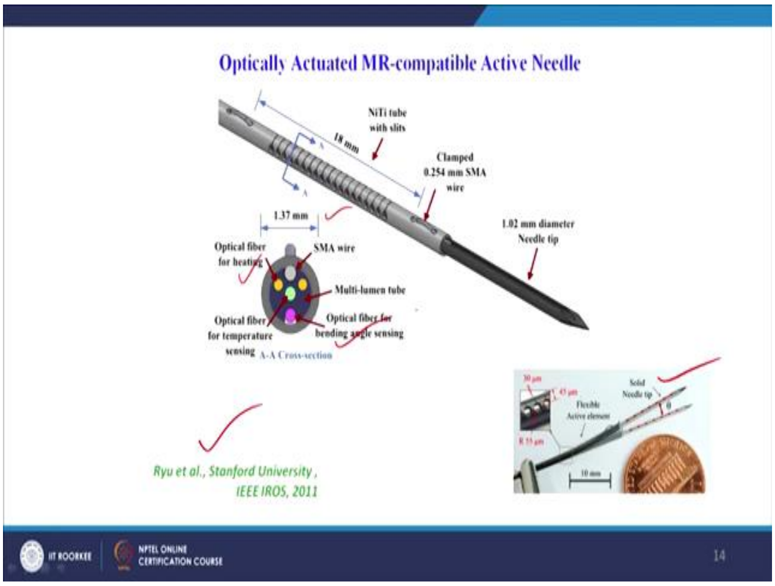

And the other needle design is proposed by Ryu et al from Stanford University. So, he has proposed the system which he is shown here which is of precisely good size here which is a smaller size. So, it has been used for it will be used definitely for the surgical purpose for conventional cancerous percutaneous interventions. It can be used for the clinical procedures and this outer dia of the needle is such that it is 1.37 millimeter dia.

And it is composed of a semi wire optical fibers 3 optical fibers one for heating the SMA wire and the other one for sensing the angle bend by this needle and the other one is for temperature sensing optical fiber is for temperature sensing and this is actuated by the SMA wire that is shape memory alloy wire actuator and this is an optically actuated MR compatible active needle proposed by Ryu et al.

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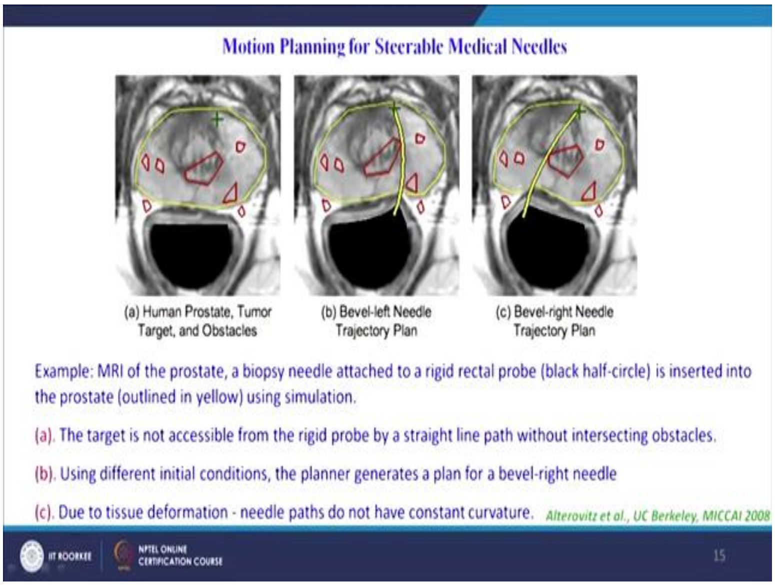

And another concept in the smart needle is motion planning for steerable medical needles. Motion planning that is a given a target we must reach by avoiding the anatomical obstacles that is a concept. So, what is the path to reach thereby avoiding the obstacles is performed by the motion planning approach.

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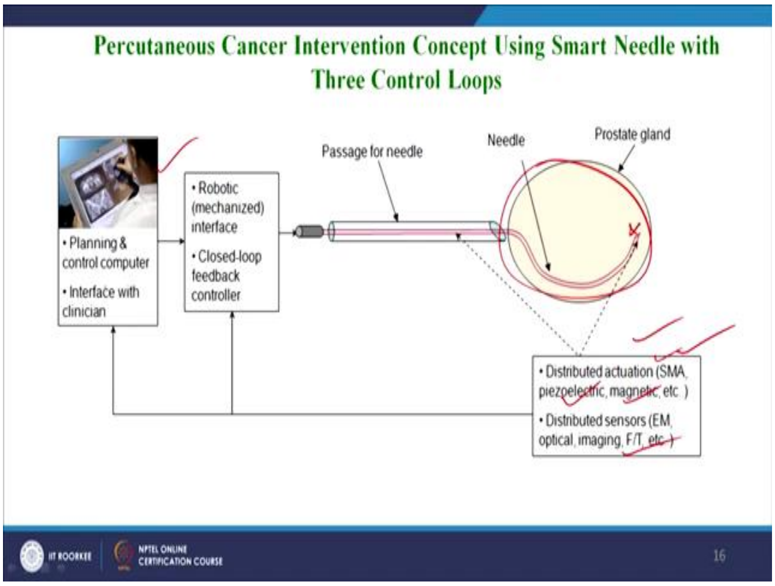

Now, there are in general proposed by Prof. Podder there are 3 loops control loops when we utilize the robot actuator or robot guided smart flexible needle. That is first loop is the inner loop which has the smart needle with distributed actuation by smart or by smart actuator such as shape memory alloy actuator, magnetic actuator or piezoelectric actuators and distributed sensors on the body of this needle such as ultra-magnetic sensor optical or imaging or EFT sensor etcetera four stroke sensor.

This is the inner loop is controlling it the needle controlling the needle only which is having the distributed sensors and actuators on its body. The second loop is a robot pushing the needle forward that is the second loop and the third loop is the physician coming into picture by providing the optimal path to reach their target without colliding with the obstacles that is by obstacle avoiding avoidance you can reach the target that path is provided optimally by the physician.

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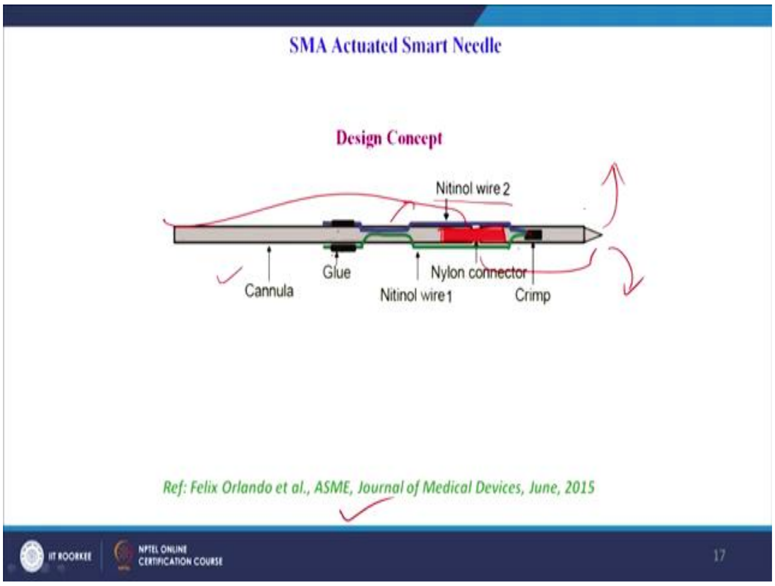

Now, coming to the concept of a semi actuated needle smart needle from my reference is given here which is the needle, which is the cannula having the SMA wire or the Nitinol SMA wire actuators connecting the needle body up to here and the needle tip or the head of the needle. They are connected by the nylon elastic element and they are bent by the Nitinol wires attach to one side of the needle body and the needle head similarly another side 180 degree apart by the same SMA wire another SMA wire attached in the opposite side 180 degree apart in the needle body and the needle head.

So, once the green SMA wire is actuated that is passing current through it gets contracted and that pins the needle in downside. Once the blue is getting heated and it gets contacted.

So, the needle moves in the upper side that needle tip and the cannula will follow the needle tip being the flexible body that is the thing that is a design concept.

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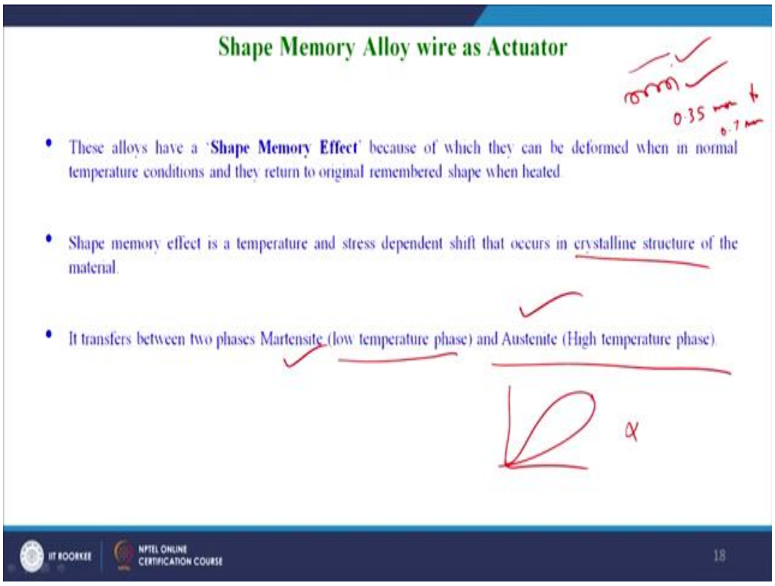

So, now coming to the part that shape memory alloy wire as actuators they are available. The shape memory wire is available in terms of straight wires or in terms of springs. Two forms they are available precisely they are varying with 0.35 millimeter dia to roughly 0.7 mm dia.

So, these alloys have a shape memory effect because of which they can be deformed when in normal temperature conditions and they return to their original shape when heated. Shape memory effect is a temperature and stress dependent shift that occurs in their crystalline structure of the material. Due to this shape memory effect they have the variation in temperature from low temperature phase called Martensite to the high temperature phase called Austenite.

So, due to this temperature change they have this capability that due to the crystalline structure change they have the temperature phase change from low temperature martensite to high temperature austenite and they have non-linearity due to the hysteretic effect that is the heating time and the cooling time are not the same. Heating time is different cooling time is different and hence the non-linearity in controlling the SMA wire happens.

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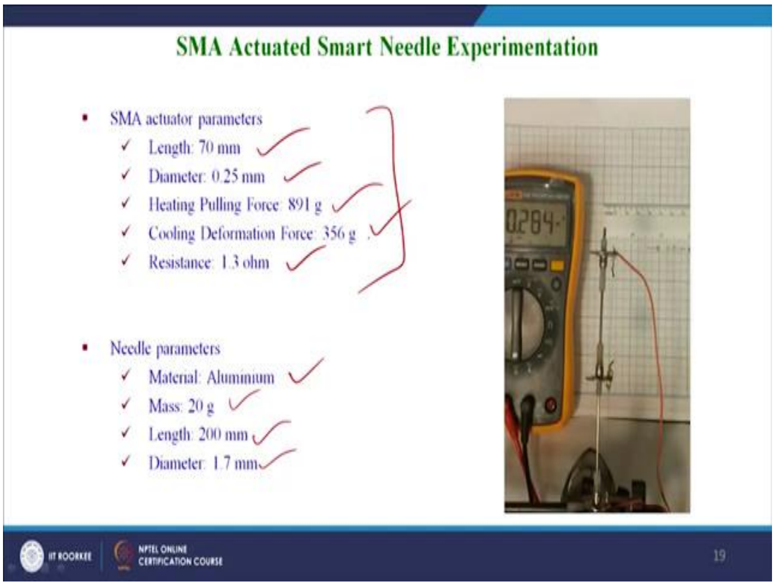

Now, coming to this one what you can see here is the proposed needle I have used in my study is of length 200 millimeter, diameter 1.7 millimeter, mass 20 gram made up of the material aluminum and the SMA wire actuators are attached to this needle in a distributed way such that each SMA wire is of length 70 millimeter, diameter 0.25 millimeter and heating pulling forces 891 gram, cooling deformation forces 356 gram and the resistance is 1.3 ohm ok.

As you can see here the SMA wire is heated by passing current through it in the range 0 to 0.7 ampere and you can see the needle tip deflection which is varying from 0 to nearly 2.5 centimeter and it has been released. So, that it can go back to its original state. This is the pulling force how the SMA actuators have during the contraction so that the needle can be bent to have the tip deflection varying from 0 to 2.5 centimeter.

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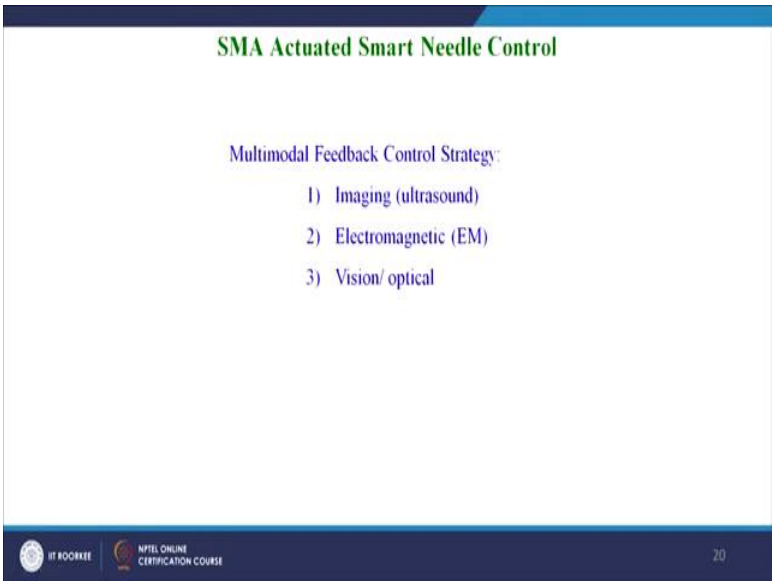

Now, coming to this we see multimodal feedback control strategy that is the how we control. Now coming to the control part we did a simple PID control of this shape memory alloy actuated needle with three feedback modalities one is with imaging that is imaging feedback through ultrasound feedback modality another one is with electromagnetic sensor modality. The other one is the vision feedback modality.

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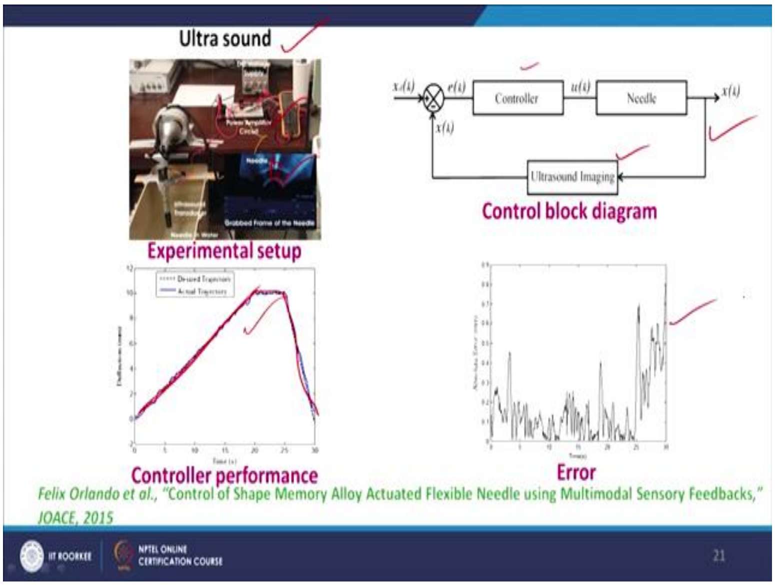

Now, we see here the results the controller performance in tracking a given decide trajectory which is increasing the length stay there then come back. This is a decide trajectory given and the system performance during this with the ultrasound imaging feedback where this is the needle tip is shown here.

These experimental setup is shown here and what we observed is where this control scheme control is a PID controller and the feedback is obtained the needle tips actual position is obtained from the ultrasonic ultrasound imaging feedback modality and we have observed from the controller performance the tracking is reasonable with the accuracy, that is our root mean square error coming out to be 0.28 millimeter.

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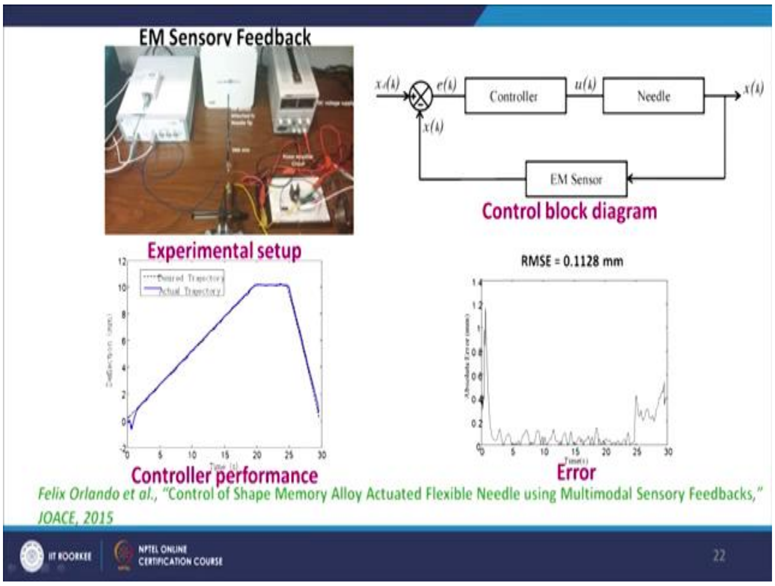

Similarly, with the electromagnetic sensory feedback where the experimental setup is shown here and this is a tracking system where we attach the electromagnetic sensor on the tip of the needle shape memory alloy actuated needle. We have obtained with a control strategy using the electromagnetic sensory feedback we have observed the performance shown here with the root mean square error coming out to be 0.1128 millimeter. The error plot is shown here.

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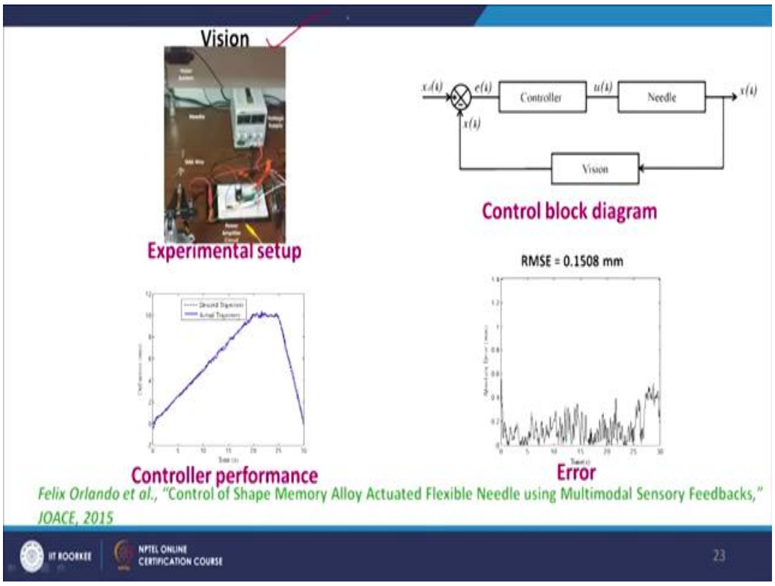

Similarly, with the vision feedback that is through camera feedback of the needle tip we have observed the controller performance like this with the vision feedback. Where the root mean square error is 0.1508 millimeter which is better than ultrasonic modality, but lesser than the electromagnetic sensory feedback and in the clinical scenario electromagnetic sensory feedback is the 1 that is used as the standard to compare the other feedback modalities such as vision and ultrasound imaging feedback.

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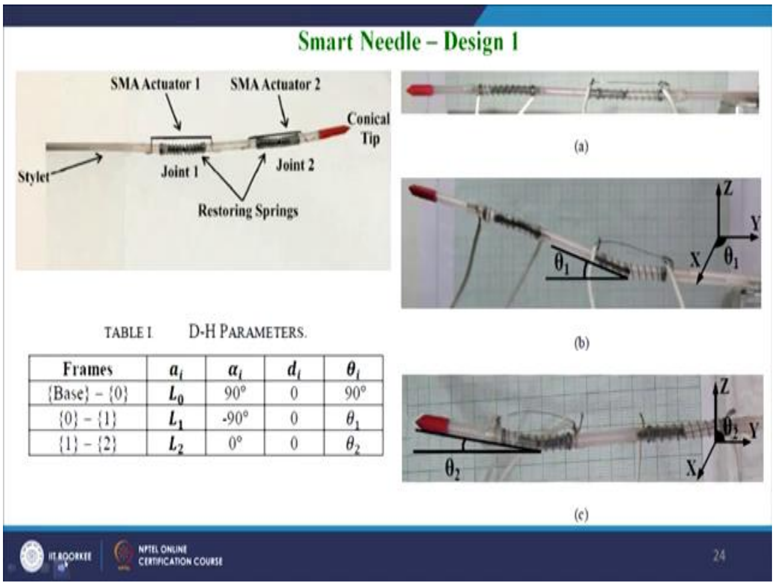

Now coming to the smart needle design 1; so, here we have performed the design of the smart needle using springs at the joints to have the fluxing back capability and the actuators at each joint is by shape memory alloy actuators 1 and 2 there the wires. And this system has 3 degrees of freedom basically it has 2 degrees of freedom which is shown here that is θ_1 and θ_2 it is a 2 degrees of freedom system θ_1 and θ_2.

The schematic of the needle is shown here developed a needle is shown here which is an active needle and it is of a diameter 0.5 centimeter, that is nearly 5 mm. It is a outer dia of this needle and it is actuated by the SMA wires and attached with springs to have the retracting capability and the D-H parameter of this mechanism or the a smart needle mechanism is shown here.

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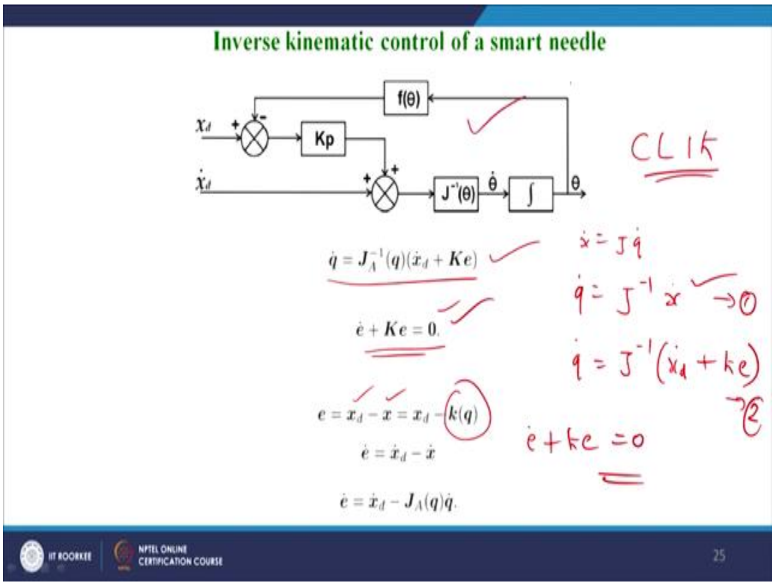

Then it has been controlled through inverse kinematic control of a smart needle. It has been controlled through inverse kinematic control provided by the closed loop inverse kinematic algorithm. Where the control law is $\dot{q} = J^{-1}(\dot{x}_d + k_e)$. Where e is the error between the desired position and the actual position of the needle tip and the actual position is given by the power kinematics. Another desired position is one we are feeding it and the x e dot derivative of the e is given by $\dot{e} = \dot{x}_d - \dot{x}$.

And now we end up with the first order error dynamic equation which shows that the error converges to 0 as the time tends to infinity. How we get this? Error dynamic equation because $\dot{q} = J^{-1}\dot{x}$ likewise the control law is $\dot{q}$ equal to this we know from the inverse kinematics point of view, that is $\dot{x} = J\dot{q}$ from which $\dot{q}$ is given by $\dot{q} = J^{-1}(\dot{x}_d + k_e)$. So, equating equation 1 with equation 2. Equating 1 and 2 we get $\dot{e} + ke = 0$, which is a first order dynamic error dynamic equation which proves that this control law is a stable control law.

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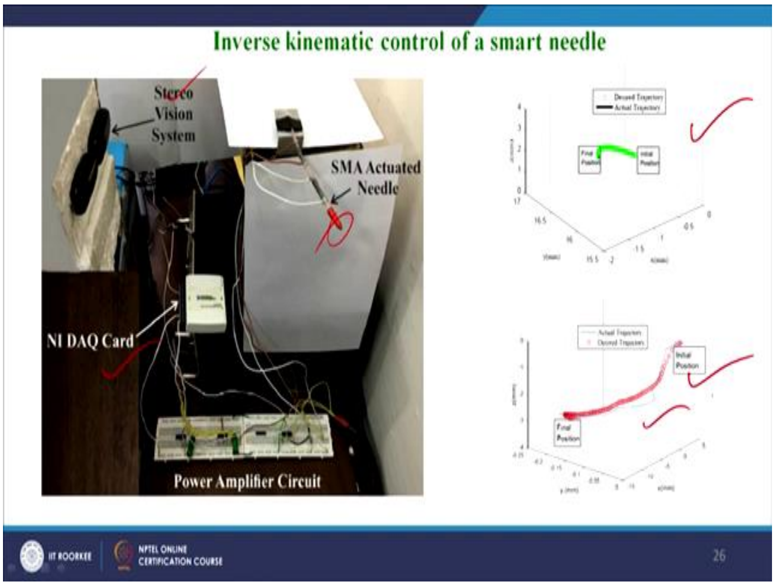

And this is a experimental setup we have utilized with a stereo vision system to predict the needle tip of the SMA actuated needle in our setup and it has been interfaced through NI DAQ card and the simulation result and the experimental result are shown here. Where the simulation is performed in MATLAB M file and the experimental 1 is performed with the lab view platform. Thank you with this we wind up this lecture and in the second lecture next lecture we will be seeing design tool as well.

Thank you.