Robotics: Basics and Selected Advanced Concepts

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Lecture - 26
Flexible robots

Welcome to this NPTEL lectures on Robotics Basics and Advance Concepts. In this week, we have we are looking at Redundancy in Robots and how to resolve this redundancy ok. In the last two lectures, we looked at hyper redundant robots and also we looked at the human arm and saw what the redundancy is used in human arm for ok.

In this lecture, we will look at a flexible robot, which is made to be extremely redundant ok. So, how do we resolve the redundancy in flexible robots? Ok.

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- Acknowledgements
  Ashwin K P – Actuated endoscopic end-effectors
  Soumya Kanti Mahapatra – Cable driven robots
- Funding by RBCCPS

So, quick acknowledgement this is the work of Ashwin and Soumya Kanti Mahapatra students in our robotics lab and the main funding is from the robot bosh center for cyber physical systems.

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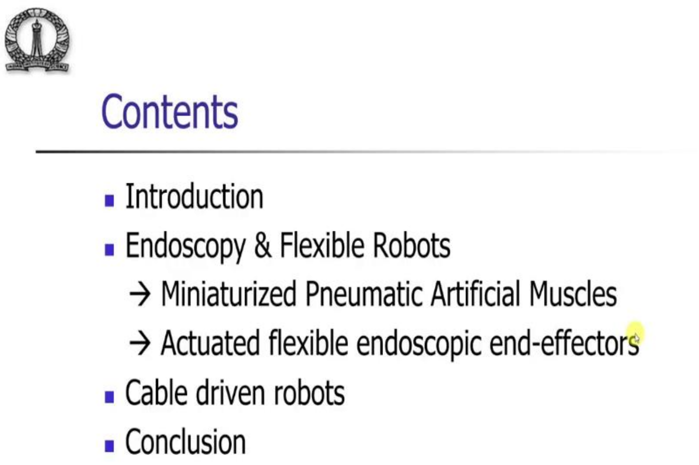

Contents

- Introduction
- Endoscopy & Flexible Robots
  - → Miniaturized Pneumatic Artificial Muscles
  - → Actuated flexible endoscopic end-effectors
- Cable driven robots
- Conclusion

So, the contents of this talk at introduction, then we will look at a place where there is extreme flexibility ok. So, this is in an endoscope. So, we will look at endoscopy and flexible robots, then we will look at what are called as miniaturized pneumatic artificial muscles. And then you will see how we can use these miniaturized pneumatic artificial muscles to make an actuated flexible endoscopic end effectors and then we will look at cable driven rob robots and finally, conclude this presentation.

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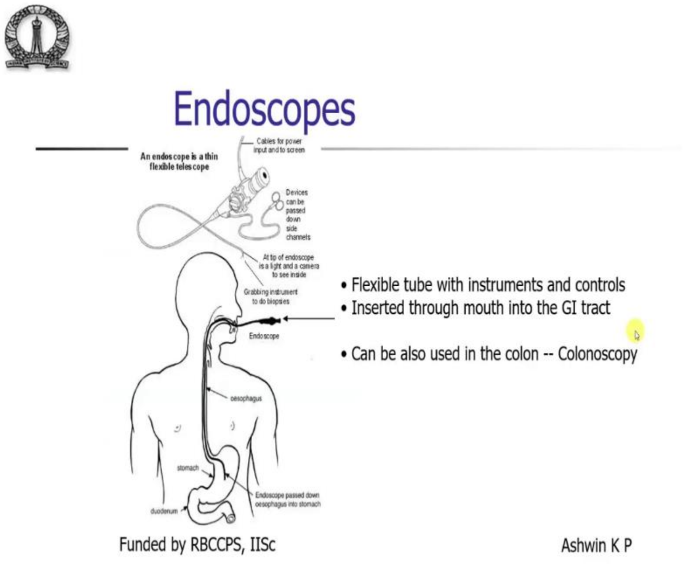

Endoscopes

- Flexible tube with instruments and controls
- Inserted through mouth into the GI tract
- Can be also used in the colon -- Colonoscopy

Funded by RBCCPS, IISc

Ashwin K P

So, what is an endoscope? So, basically it is a thin flexible telescope ok, that is the way it is understood. So, what it is that we have this long cable like structure, it is very flexible at the tip of the endoscope there is a light and a camera ok. So, the idea is that you send this device through your mouth, through your GI tract into the stomach region and then you can take pictures ok.

So, this flexible tube with instruments and control is inserted through the mouth into the GI tract ok. Similar thing is also used to insert in your colon for colonoscopy ok. So, what is the purpose? The purpose is this flexible tube has a camera and some light at the end and you can take pictures of what is happening in your stomach. So, if you have cancer or if you have ulcers, you can take pictures and then the doctor can figure out how to treat you properly ok.

So, this is an extremely flexible tube. So, we want to look at how to model these things. So, in one of the lectures earlier I had shown you how we can model it using tractrix based algorithm, discriticized into small small pieces and show how this endoscope can move inside your GI tract. In this we are looking at the end of the endoscope basically, so we want to look at how we can add something to the endoscope to make it more useful and that will be a flexible robot ok.

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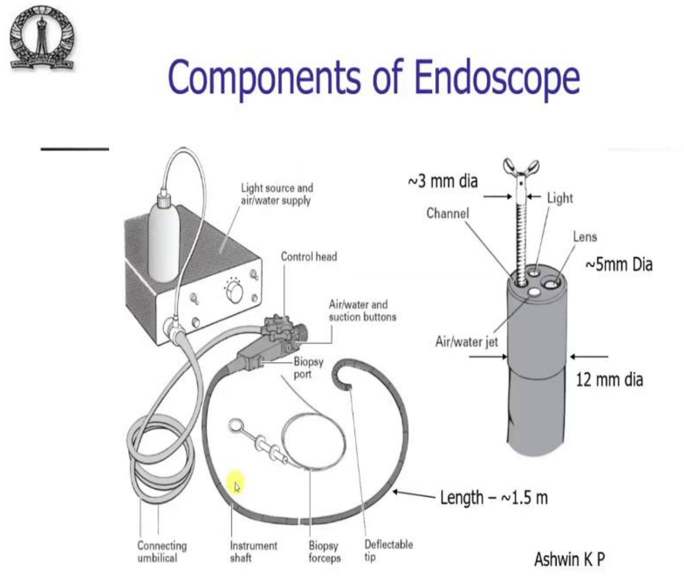

Components of Endoscope

Ashwin K P

So, let us quickly go back and see what is an endoscope. Basically, as I said it is a flexible tube of length of approximately 1.5 meters ok. There is connecting umbilical cord which connects to the light source and air supply there are these control heads. So, 2 knobs which you can rotate and then the tip of this tube can rotate, look at the pictures of this inside that stomach region from different directions ok.

So, it has like 2 degrees of freedom and these 2 knobs basically transmit the rotation of these knobs through some cables all the way to the end. There is also a channel which is called the biopsy port through which you can send an instrument like this ok. So, in this instrument there is a long thin wire and at the end of the wire you can have something like a grasper or a scissor or something.

This is very small it is about 3 mm diameter. So, you can push this and then when you are looking at and you see something of interest you can take a sample ok. The other end of the endoscope which is here, which is what we will look at in more detail little bit later ok or we want to modify. There is a way to project light using some fiber optic cables ok, fiber optic system and then we have a lens and a camera which you can take pictures.

There is also a channel to inject water and air, because when you are putting this endoscope through your mouth and in through the GI tract, there could be some food or some other particles things there. So, when you see that you can inject some water or air to remove it so, that you can pass through it ok, this whole thing is about 12 mm diameter, the lens is approximately 5 mm diameter and this is about 3 mm diameter ok.

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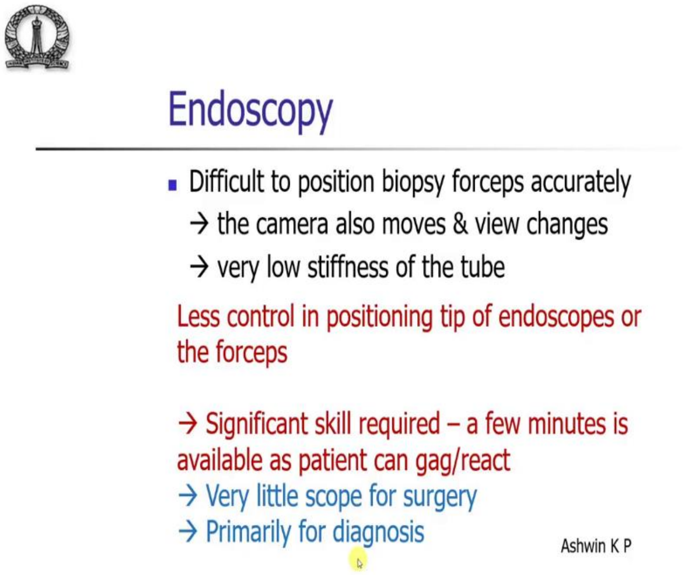

Endoscopy

- Difficult to position biopsy forceps accurately
  - → the camera also moves & view changes
  - → very low stiffness of the tube

Less control in positioning tip of endoscopes or the forceps

→ Significant skill required – a few minutes is available as patient can gag/react
→ Very little scope for surgery
→ Primarily for diagnosis

Ashwin K P

So, what are some of the problems in current endoscopy? It is very difficult to position the biopsy forceps accurately ok. So, as you can see there is this biopsy forcep, so something is coming out of here which is extending a little bit. Now, if I want to position this I have to move this whole head ok. I have to move this whole head using this control heads these two knobs, but when you move this head the view also changes ok.

So, the camera is seeing something else and the view changes, the tube is also very very less stiff ok, so it is of low stiffness. So, when you are projecting this grasper and if you want to move it will not position very accurately. So, in summary what we have is we have very little control in positioning the tip of the endoscope or the forceps ok. It is mostly used for diagnosis.

So, you can take pictures. So, you do not need to position very accurately which you need if you want to take a sample. A lot of skill is required to take these samples or to position this biopsy forceps accurately; however, we have only a very little time ok. We have a few minutes to do this task, because when something is put through your mouth you tend to vomit or tend to gag and you want to throw out the things. So, there is very little time.

So, although they put anesthetic and things like that, but nevertheless you cannot keep the endoscope inside your GI tract for too long. And as a result there is very little scope for surgery, ideally we would like to do some small minor surgery not only take samples, but maybe do some surgery there. Currently it is only used for diagnosis primarily for diagnoses, but we want to take samples we want to do surgery ok.

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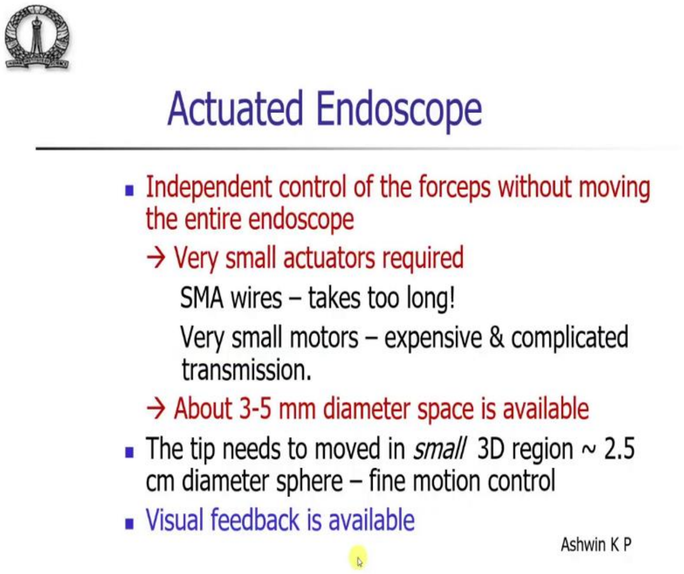

Actuated Endoscope

- Independent control of the forceps without moving the entire endoscope
  - → Very small actuators required
    SMA wires – takes too long!
    Very small motors – expensive & complicated transmission.
  - → About 3-5 mm diameter space is available
- The tip needs to moved in *small* 3D region ~ 2.5 cm diameter sphere – fine motion control
- Visual feedback is available

Ashwin K P

So, if you want independent control of the forceps without moving the entire endoscope ok, we need to have very small actuators. So, as I said the whole endoscope head is 12 mm, the channel through which you send this instrument is 3 mm, maybe you can increase it a little bit, but you cannot increase it too much ok. So, we need very thin small actuators, one option is to use what are called shape memory alloy wires ok.

Shape memory alloy works that if you heat it by say passing some current, it will contract it will move it will actuate something. Heating is very quick, but if you want to move it again next time, you have to cool it back to some temperature and that takes too long. So, shape memory alloys are not very useful we cannot of course, have motors, you know it is very very expensive and complicated to have motors and transmission which can move through the small channel ok.

Maximum about 3 to 5 mm diameter is available ok. So, we need some actuator which can be used to position that grasper or the forceps independently of the head of the endoscope ok. What are some of the advantages that we have? We need to move the tip very small amount we need to move in a small 3D region. So, something of the order of 2.5 centimeter diameter sphere on the surface of a sphere, but we need fine motion control, we need to move it little bit, but accurately.

The other big advantages we have visual feedback available. So, there is a camera which is looking at whatever you are doing. So, you can correct if you are making a mistake, if you are going in the wrong direction you can correct it. So, visual feedback is very important and it is available already.

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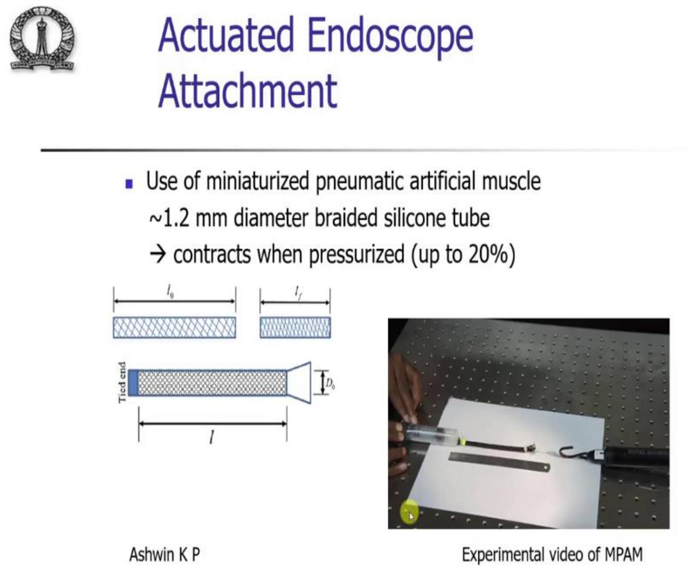

Actuated Endoscope Attachment

- Use of miniaturized pneumatic artificial muscle
  ~1.2 mm diameter braided silicone tube
  → contracts when pressurized (up to 20%)

Ashwin K P

Experimental video of MPAM

So, what we proposed in our robotics lab is to use what are called miniaturized pneumatic artificial muscles ok. We want to make the endoscopic attachment independently actuated, and the actuator that we have chosen is this miniaturized pneumatic artificial muscle. So, we can get these tubes which are made of silicon and then braided with a much harder cable or a net like material of the order of 1.2 mm ok.

So, it is reasonable you know we want something like 5~6, mm diameter entire assembly, our actuators are now 1.2 mm. The important thing is these actuators can contract when pressurized by up to 20 percent. So, basically initially the tube looks like this, this is the silicon tube with some brading of a tougher material on the outside, it is of l_0, when you pressurize it will contract to some l_f ok.

So, that is what is happening. And I want to show you a video. So, this is this miniaturized tube, we are going to pressurize this with air using a syringe one end there is a small load to keep it straight ok, and then we will see what happens. So, when you are pressurizing it, you can see that the yellow end or one end is slightly moving backwards and you can see how much it has moved when the pressure is released.

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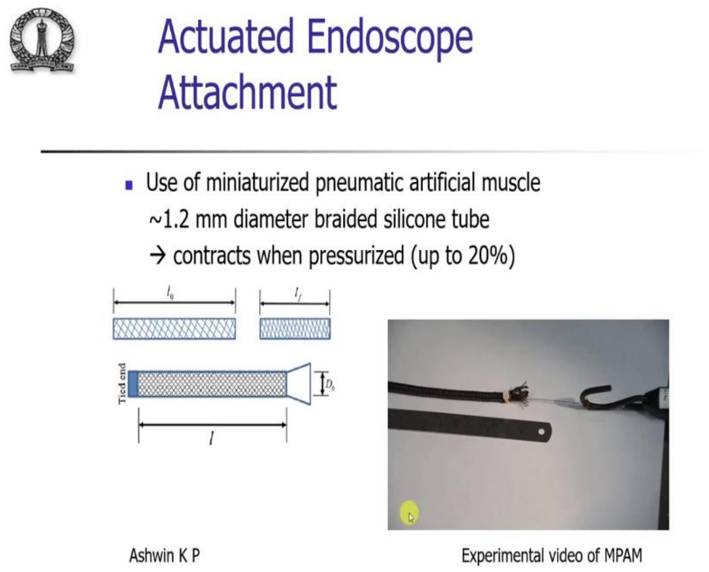

Actuated Endoscope Attachment

- Use of miniaturized pneumatic artificial muscle
  ~1.2 mm diameter braided silicone tube
  → contracts when pressurized (up to 20%)

Ashwin K P

Experimental video of MPAM

So, as I mentioned it can contract by up to 20 percent of its length ok, which is quite a bit and the pressures are also not very high, we can see that the pressure which the student is applying is basically whatever is there in a syringe.

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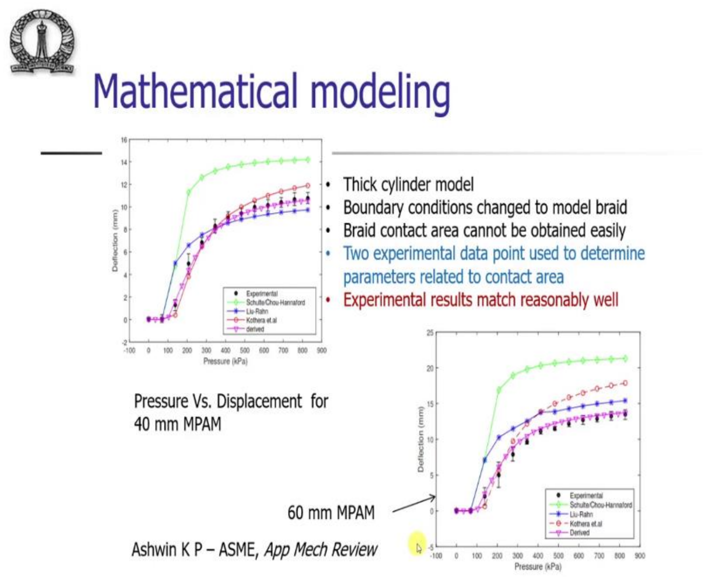

Mathematical modeling

- Thick cylinder model
- Boundary conditions changed to model braid
- Braid contact area cannot be obtained easily
- Two experimental data point used to determine parameters related to contact area
- Experimental results match reasonably well

Pressure Vs. Displacement for 40 mm MPAM

60 mm MPAM

Ashwin K P – ASME, *App Mech Review*

So, first thing is we need to make a mathematical model of this contracting tube of this miniaturized air muscle ok, it is called muscle. Because like muscles these things contract when you apply some force or pressure ok. So, we made several mathematical models, some of the elements of the mathematical model is we assume it to be a thick cylinder ok.

The diameter of the tube is quite small and the silicon material is also approximately of the orders of the diameter. So, we cannot use traditional thin cylinder models. We also need to apply some boundary conditions because the braid does not expand or contract when you pressurized it.

It is also very hard to find what is the contact area of the braid, because this wire this nylon wire is wound around this silicon tube, at some places there is no wire. So, what we did was we use 2 experimental data points to estimate the parameters which are the contact area and some other things ok.

And then we looked at if I apply some pressure which is some 0 to about 800 kilo Pascals, we see what is the deformation of this tube ok, as same as the experiment. So, you can measure the deformation. So, if you have a 40 mm long tube and then when you pressurize it to let us say 200 kilo Pascals.

The experimental value is this dark value, there is a band which means this is the mean and these are the variation around the mean. It is of the order of 5 millimeters and as you keep on increasing the pressure after a while it saturates. So, for example, let us at 800 kilo Pascals it is like 11 millimeter is the contraction, in a tube which is 40 mm long.

So, the plot of the experimental values are shown in this dark colored with a bar and then like anything that many people have worked on this. So, they have various models of this miniaturized tubes ok, silicon tubes contracting when you apply pressure. So, there is a Schulte Chou Hannaford model which is this green ok, and that is predicting much more than a what the experiments are showing.

There is a model given by Kothera or Liu Rahn ok. So, all these are very close to that, but nevertheless there is a difference between experiment and the model what it is predicting. We developed a model which is this triangle ok; purple colored triangle and you can see that this model is very very close to the experiment ok.

I do not want to go to the details of the model, but basically we used a thick cylinder model, we put some proper boundary conditions because of the braiding, then we use some experiments to estimate the area of contact and so on. And as you can see at different lengths, this is for 40 mm, this is for 60 mm again here our model which is this inverted triangle ok, purple color is very close to the black which is the experimental value.

The others are little bit far away ok. So, we have now a mathematical model, which appeared in this ASME applied mechanics review of a pneumatic air muscle ok, miniaturized pneumatic artificial muscle when you apply pressure. So, this model is required because we need a model to if we want to do control later on ok. We need to know how much pressure to apply such that this much contraction happens ok.

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Actuated forceps

CAD model of actuated forceps

Developed hardware

- Three MPAM arranged 120 degrees apart
- Actuation of one, two or three at a time
- Varying pressure gives different contractions in the air muscles
- End-effector can move on the surface of a sphere.

IFToMM World Congress 2015

We cannot keep on using experiments. So, once we have this mathematical model, we have some good idea as to how much it will contract when you apply pressure. We use 3 such tubes arrange 120 degrees apart ok, and we made a CAD model of an actuated forceps. So, this is the forceps, there is a holder here and there is an initial holder here, in between that there are these 3 artificial muscles ok.

There is a spring on the outside because the spring helps in bringing it back ok. There is also an innerspring which also a gives some stiffness. So, this inner and outer spring gives some stiffness to this whole assembly and helps in bringing it back when you release the pressure. There is this tube through which you supply air and then there are this one central tube through which you can send and at the end you can have forceps or any other tools that you want ok.

So, we developed a CAD module consisting of let me repeat three MPAMs -- miniaturized pneumatic artificial muscles arranged 120 degrees apart, if you actuate one, two or three at a time it will move ok. So, for example, if I actuate the top one this one will contract and this tip will go upwards in one direction if I actuate two of them then the tip will move in the resulted direction.

We can also vary the air pressure inside the tube and make it move less or more because the contraction depends on the air pressure that you give. So, basically what we have? We have these three and we can actuate one, two or three all three at a time and then we can make it move on the surface of a hemisphere or surface of a sphere ok. So, this CAD model was implemented and this is how the hardware looks like.

So, this is a little bit bigger than 5 mm or 6 mm, actually this is more like 7 mm which we constructed. So, there are these three, then there is this grasper and then there is a small tube which you can actuate this grasper and this whole assembly can move on the surface of a hemisphere ok, when you actuate this artificial muscles, when you pressurized these artificial muscles.

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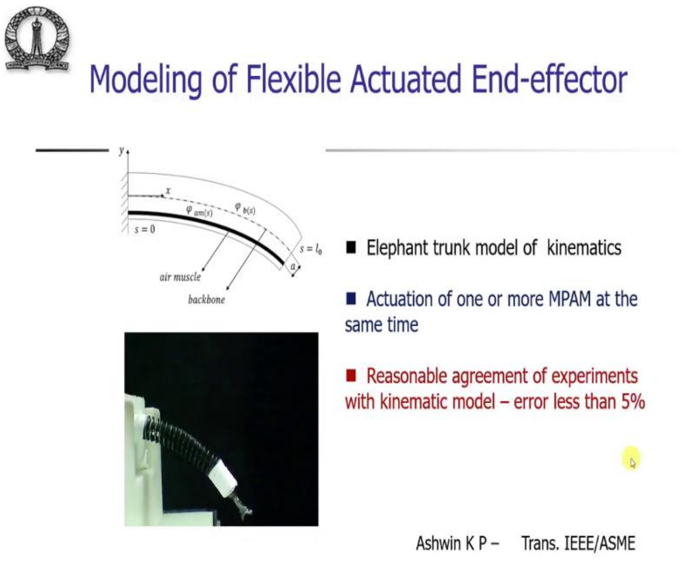

Modeling of Flexible Actuated End-effector

- Elephant trunk model of kinematics
- Actuation of one or more MPAM at the same time
- Reasonable agreement of experiments with kinematic model – error less than 5%

Ashwin K P – Trans. IEEE/ASME

And how do we model where it will go when you actuate these muscles? So, there is something called as an elephant trunk model in kinematics of continuum robots or flexible robots. So, elephant trunk model consists of that there is an arc from s equals to 0 to l, then there are these artificial muscles then there is a backbone ok. So, this backbone is more stiffer. So, the backbone is that in inside spring.

So, when you actuate this muscle, because this muscle contracts, this backbone will bend ok. So, there are these parameters of distance from the backbone a, and the which we know and then based on this parameters and this equation of this backbone, we can estimate where the tip is get. So, it turns out this elephant trunk model gives a reasonable estimate of where the tip should be ok, except some portions are straight here everything is elephant trunk.

So, if you account for all these small small variations. We can estimate where the tip of this forecep or the grasper will be when you apply air pressure using this elephant trunk model ok. It turns out the error is less than 5 percent ok. So, we now have of model which tells you if I apply pressure how it will move and where it will move ok.

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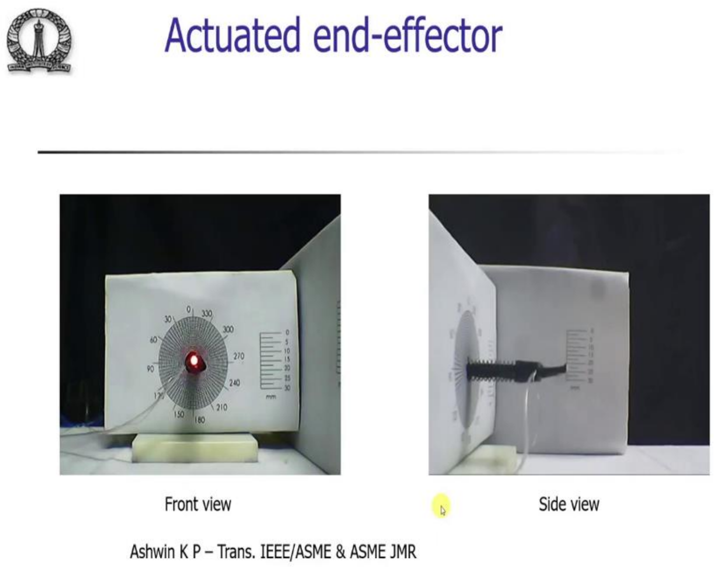

Actuated end-effector

Front view

Side view

Ashwin K P – Trans. IEEE/ASME & ASME JMR

So, we build this device which I showed you and I am going to show you 2 videos of this device being actuated by air pressure. So, the air is coming through these tubes and I will show you 2 views. So, from the front it moves and from the side you can see how this you know actuated end-effector moves, when you pressurize the air.

And as we can see this scale is between 0 and 30 mm from both sides, we want to move about 2.5 centimeters 25 mm ok. So, let us show this video. So, the motion of this end can be seen more clearly because we have put an LED at the end. So, front view shows is LED and we can see as you pressurize and get different air pressure as well as actuate either 1, 2 or 3 or 3 at in some order, this head will move the tip will move.

So, I can move in any direction basically on the surface of a sphere from the center and the movement is roughly about plus minus 2.5 centimeters maximum displacement. This is small displacement, but this is more than enough ok. In this inside the stomach we do not need to move much, although it is not shown in this video the motion was actually controlled by a joy stick.

So, when you move the joy stick ok, then the this end this actuated end-effector moves in the direction of the joystick and then you can apply more or a less pressure also. So, the video will play for a longer time, but I am going to stop here, but the basic idea is by applying air at pressure in these 3 tubes, I can make it move in any direction on the surface of a sphere ok.

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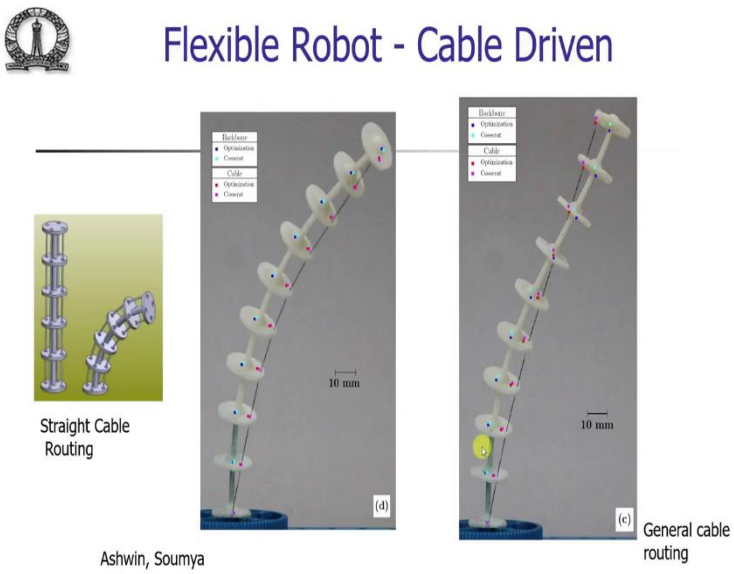

Flexible Robot - Cable Driven

Straight Cable Routing

Ashwin, Soumya

General cable routing

Now, let us continue, let us look at another way to actuate a very small end-effector ok, and instead of using air we want to actuate an end-effector using cables. So, what we have here is a flexible back bone, which is this central back bone and on this back bone there are these disks with holes ok, as through this hole you can pass a cable ok. So, these are wires thin very thin wires ok.

And as you pull this wire, this whole structure will bend and the basic idea is that if you have several such cables, and if you pull these cables in a proper way we can also make the end move on the surface of a sphere or can even trace a curve on a surface of a sphere ok, by suitably choosing which cable to pull. So, for example, this one shows 4 cables. So, if I pull this cable it will bend this way, if I pull this cable it will bend this way, if I pull this cable it will bend towards you and so on ok.

So, there are various ways to send these cables. So, this shows a straight cable routing meaning that each hole is on one on top of the other and the cable is straight ok. So, first thing is how do we model such a system? So, there are various modeling techniques, which are there in literature there is something called as a Cosserat rod model, I am not going to go into the details of that, but this green dots shows how the Cosserat rod theory predicts, when such a flexible back bone with disks and then you pull this cable ok.

So, it just reasonably accurate to the actual experimental data, we developed another technique called optimization base model. So, basically each link here. So, this one pair between this point and this point and this point and this point can be considered to be a 4 bar linkage and then one of the links of this 4 bar linkage, changes length when you pull the cable and this optimization based approach is using this 4 bar leakage ok.

The Cosserat rod model uses many other parameters, basically the E value, the Young's modulus and various other values of this back bone. We do not use that we will use only the geometry of this linkage, this 4 bar linkage and we also developed this optimization base model and then we compare with the Cosserat rod model ok, and also the experiment.

So, you can see here this is how experimentally it looks like, when you pull it the dark blue is our optimization base model, the light blue is the Cosserat rod base model, for the cable also the location of the cable which is passing through this hole, where should the cable be based on optimization and base on Cosserat. You can see that they are very close to each other ok.

We can also extend this model, when the cable is not straight ok, meaning that it does not go from one hole to other hole all the way straight. We can go from the first hole to the 2nd and then it can be twisted. So, it can go to some other hole and we can have what is called as a general cable routing.

So, that cables are not straight. So, when you pull such a cable the shape of this back bone is different. So, you can see it is bending like this and then goes bends in some other direction, when you pull this cable. So, again the theory should be able to predict what is the shape of this back bone ok, where these points are and as you can see now the optimization Cosserat rod model and the actual things are deviating a little bit ok.

So, our optimization which is dark blue which shows where the center of these back bones should be, the disc center and where this back bone is attached to the disc. it is closer to the experiment likewise what is the location of the cable? How the cable will twist? Or where the cable point will go connection point will go? Again there is some difference now and we claim that our optimization model is more accurate sometimes ok.

It is not everywhere it is not that good or bad ok, here the Cosserat rod and our optimization is very close to each other ok. So, whereas, here it is slightly far and our optimization is closer. So, this is a work in progress, but we are developing this flexible robots which are cable driven ok, and this whole back bone and these discs are 3D printed it is very easy to assemble and although it is slightly bigger right now, but we can hope to make such robots which are very small and actuated easily.

So, as you can see depending on the cable routing and the number of cables I can move the tip in some desired path ok, and the goal is to find a relationship between the path of this head tip and how much to pull the cable. It has also desired to find out what happens when you have different cable routing ok. What is the shape that this a flexible robot will take ok.

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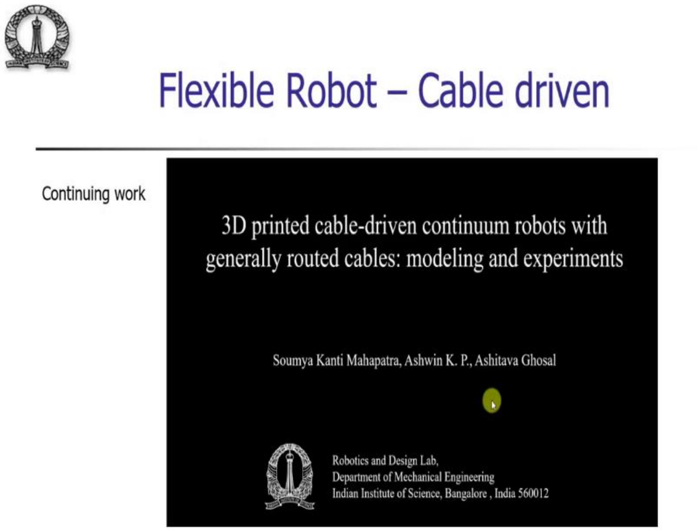

Flexible Robot – Cable driven

Continuing work

3D printed cable-driven continuum robots with generally routed cables: modeling and experiments

Soumya Kanti Mahapatra, Ashwin K. P., Ashitava Ghosal

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So, this is as I said this is a work in progress, but I am going to just show you what the students Soumya Kanti Mahapatra and Ashwin did. So, this is a 3D printed cable driven continuum robot with generally routed cables modeling and experiments ok, what all we can do.

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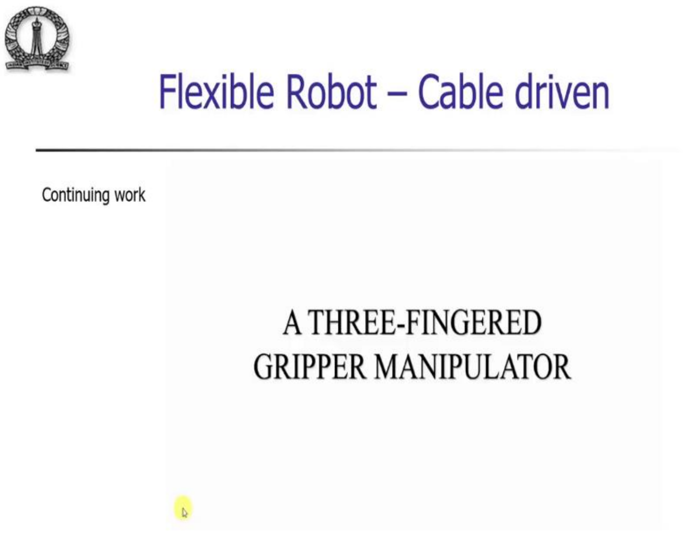

Flexible Robot – Cable driven

Continuing work

A THREE-FINGERED
GRIPPER MANIPULATOR

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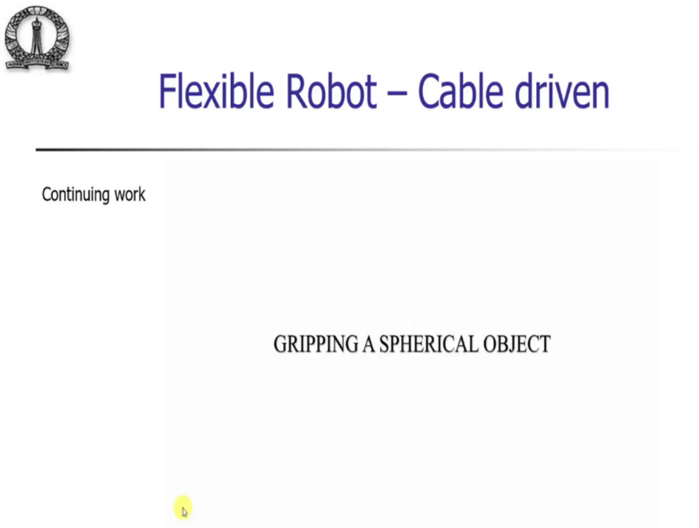

Flexible Robot – Cable driven

Continuing work

GRIPPING A SPHERICAL OBJECT

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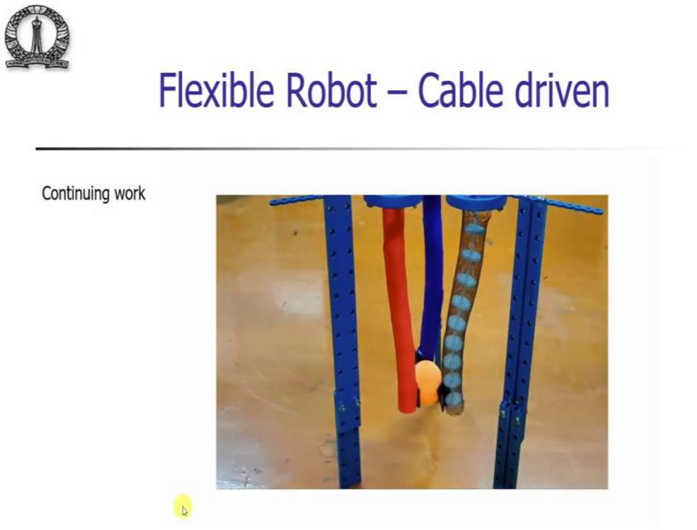

Flexible Robot – Cable driven

Continuing work

So, what is the shown is there are 3 of this thin cable driven back bones and we can use it to grip an object. So, for example we can grip a sphere and then pulling the cable or pulling the cables in differently.

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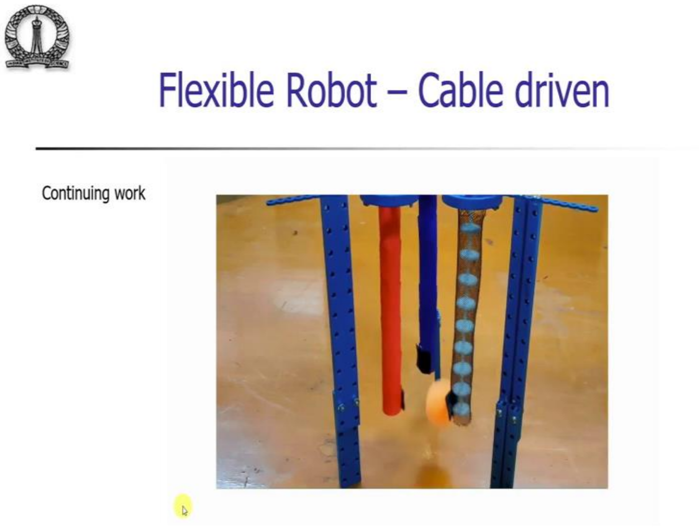

Flexible Robot – Cable driven

Continuing work

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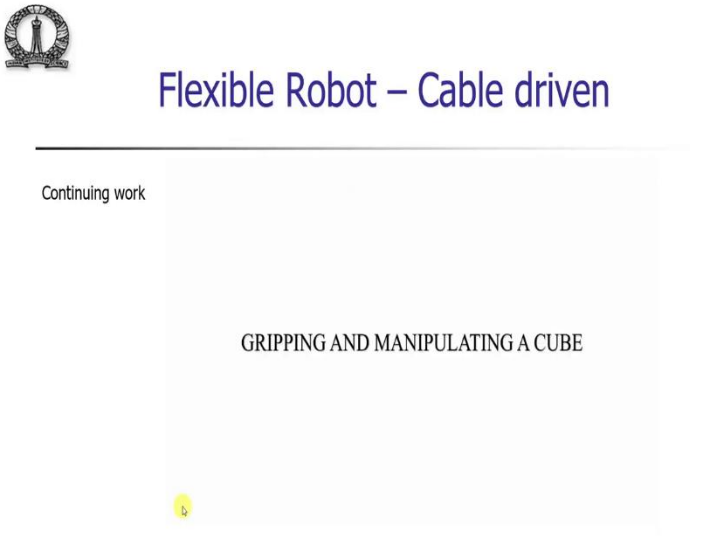

Flexible Robot – Cable driven

Continuing work

GRIPPING AND MANIPULATING A CUBE

We can make the sphere move also, we can manipulate the sphere.

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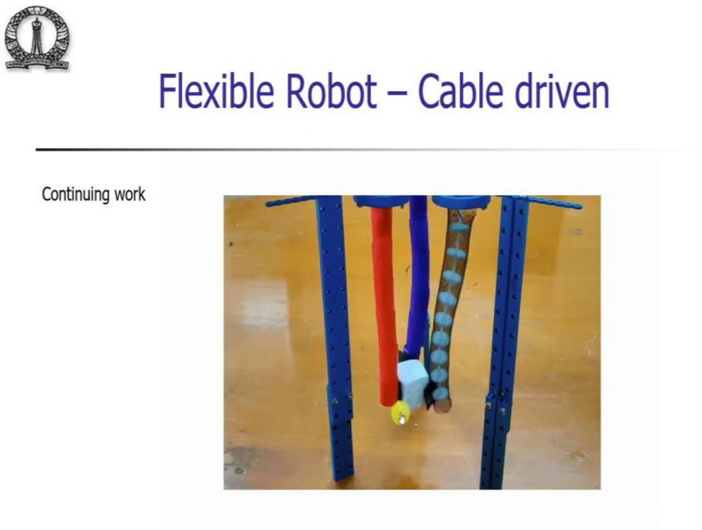

Flexible Robot – Cable driven

Continuing work

So, the next example is this 3 cable driven flexible, robots gripping a cube and then making the cube move in some way.

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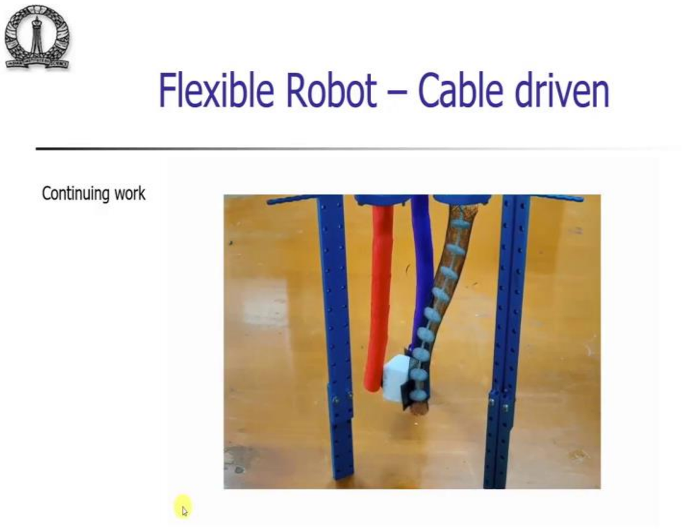

Flexible Robot – Cable driven

Continuing work

So, these black patches are nothing but some soft sponge. So, that it can hold the cube or the ball properly, they are not it is not sticking to it.

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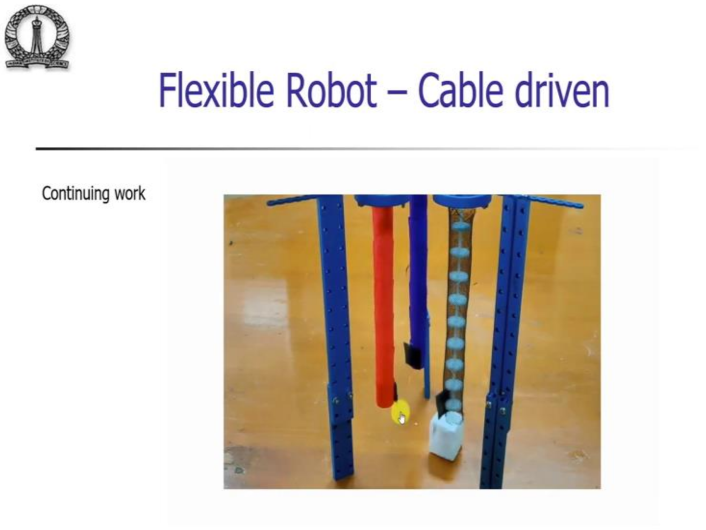

Flexible Robot – Cable driven

Continuing work

So, as you can see when the fingers are moved apart this white cube you know cube will fall. So, what I wanted to show you is that we can have this flexible robots, which are consisting of a flexible back bone with discs through which you pass cables and then when you pull the cables, this whole flexible backbone will bend and you can now have 3 of them to grip an object and make it move to a desired position or desired orientation.

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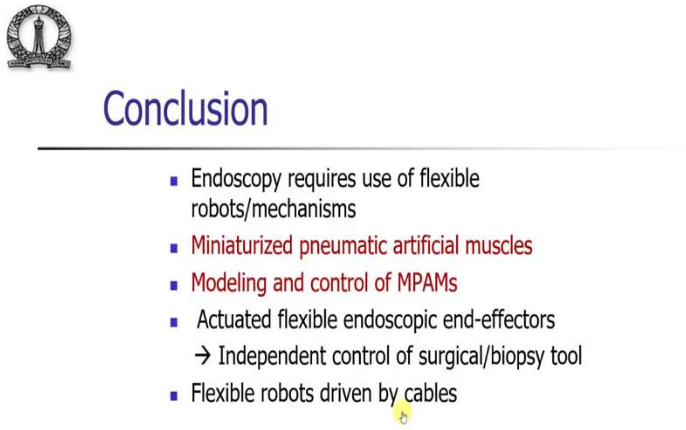

Conclusion

- Endoscopy requires use of flexible robots/mechanisms
- Miniaturized pneumatic artificial muscles
- Modeling and control of MPAMs
- Actuated flexible endoscopic end-effectors
  → Independent control of surgical/biopsy tool
- Flexible robots driven by cables

So, I am going to stop here. So, in conclusion endoscopy requires use of flexible robots or mechanisms ok. Normal endoscopy I cannot position the end and do any surgery, I can at most look at the GI tract or look at the stomach, but if I want to position I need stiffness, I also need an independent control of the actuated end-effector.

So, we can use what are called as miniaturized pneumatic artificial muscles ok. They are very thin, very small we can make a model of this miniaturized artificial muscles and then when you pressurize these muscles they contract and using 3 of them I can make the end-effector, which is the grasper or some other tool move independently of the head of endoscope.

So, we can model this MPAMs, we can even control these MPAMs by suitably adjusting the pressure and sending the pressure to which of these 3 tubes ok. So, what the goal is we want actuated flexible endoscopic end-effectors ok, which we can independently control for surgery or biopsy tool ok.

We can also make flexible robots driven by cables and I have shown you a work which is in progress, where 3 of this flexible robots with the flexible back bone and discs by pulling wires or cables, we can make this flexible robots move, it can grip an object and you can position and orient that object.