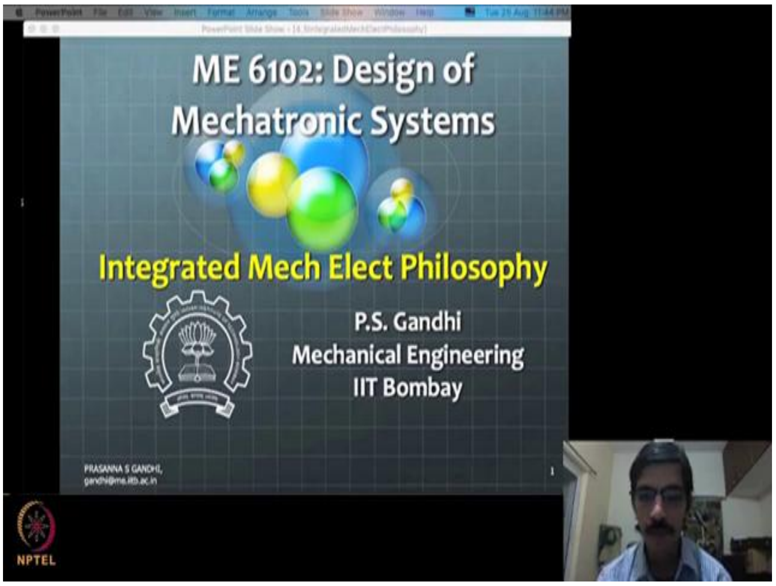
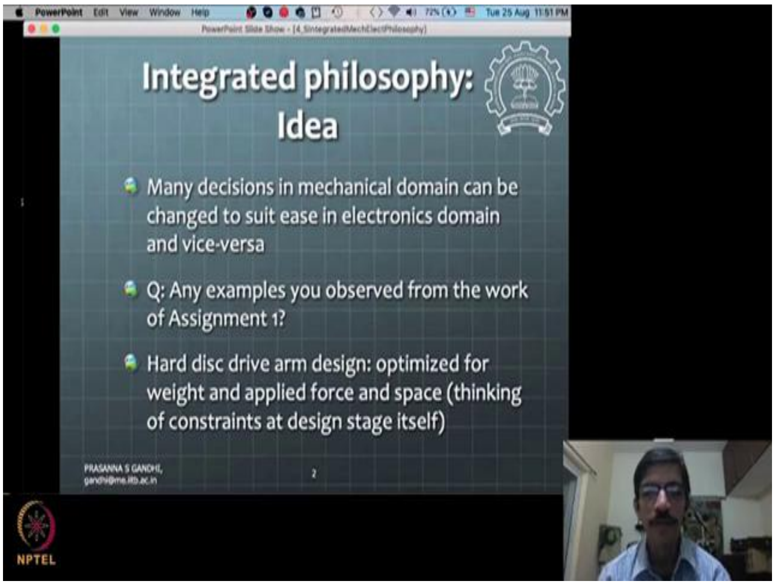
**Design of Mechatronic Systems**
**Professor Prasanna S. Gandhi**
**Department of Mechanical Engineering**
**Indian Institute of Technology Bombay**
**Lecture 09**
**Integrated Mechanical-Electronics Philosophy - Part I**

(Refer Slide Time: 00:15)




So, let us start a next lecture on integrated philosophy of mechanical and electrical domain thinking, it is a mechatronics thinking. So, far we have been discussing some part of it already, but let us discuss it little more in, with more examples and some formal thinking.

(Refer Slide Time: 01:02)




So, we will begin this lecture with what is idea basically. So, as we have been talking about if you recall, we have said that in this philosophy, you think in one domain to ease out the things in other domain. In other words you need to think integrated in both the domains of mechatronic system like mechanical domain and electronics domain. So, typically the plant of the system would exist in the mechanical domain and mechanical plant will have, will some complexities that are coming because of the natural phenomenas.

So, for example, there is a friction phenomenon which is natural to have for any of the motion systems. Then, if you talk backlash phenomena that will be there for its transmission systems, like that some non-linearity in heat transport kind of the system, mass transport system. We have been so far looking at only motion systems, mechanical. But, you may have some systems which have other phenomena in fluid domain for example you will have flow phenomena happening in the non-linear domain.

So, considering all these effects of different phenomena that are happening in the mechanical domain, how do we think that we have to ease out control of this phenomena, in such a way that your electronics domain also has some easy way to control. So, you change something in the mechanical domain design to affect something in the electronics domain. That is a central idea.

Likewise, you can have in the electronics domain we do control. So to ease out something in electronics domain we have seen, we can do some modifications in the mechanical domain. Likewise, ease out something in the mechanical domain, you do some things in the electronics domain. For example, if you talk of this electronic fuel injection system. So, the previous systems if you know of car those were working with formula racing team, they might appreciate this little better.

The injection of the fuel into the system or engine was based on some mechanical elements which are moving in some a fashion. And that was some a complex camp based mechanism to open the fuel port to inject the fuel into the system at some particular time in the cycle of the engine operation of a automobile.

Now, this complexity of all these mechanical chains of driving the camp and affecting the fuel injection, can be taken care of by using the electronics fuel injection system. Where, by the digital command of some electronic interface, the fuel will be injected in the system. Now, this way of doing things will have a more flexibility of planning the fuel injection into the engine based on many different kind of aspects of the working of the engine and make the engine more efficient to work.

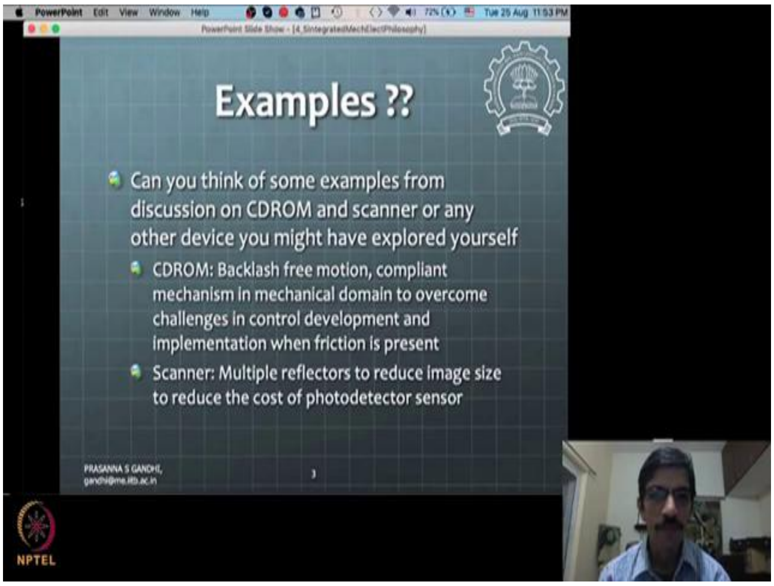
So, this is one of the ways in which you can do something in electronics domain. To ease out the complexity of mechanism that are to be used in the mechanical domain. So, like that you will find many systems are getting developed nowadays, with the electronics kind of a commands more than mechanical elements put together.

So, many machines can be operated, instead of having these complex mechanical drives you can have electronic kind of a drives. One other example, you might have heard about these type writers in the olden era where they use some make, they have very interesting mechanism used to be there for typing keys. So, you press on the key on a keyboard and the mechanism would kind of impact some letter on the paper.

So, that kind of a way of typing now can be eased out by you can see, nowadays what people are typing is based on all electronics kind of the keys. So, these are some of the examples of other direction, which so far we have not looked at. And this has a value so, this has a great value in developing efficient systems which will work very nicely in conjunction with each other and deliver whatever is demanded on desired application.

Then, this arm has been designed to optimized for the weight of it, if you see carefully. So, weight, it now one can get little bit more detail into what are the forces really coming on the arm. What are their forces that are coming on the arm is actuated by actuator. And imagine that you have this arm here.

(Refer Slide Time: 07:15)




So, we will be see that arm in the in a while but we can just see, I will just recall here there are these examples from the discussion on the CD-ROM drive and scanner, that we had already done in the class, that in CD-ROM you have a backlash free motion or friction free motion that is obtained by compliant mechanism in the mechanical domain, so that you can ease out control in the electronics domain.

So, that there are control challenges which are only are controlled with friction absolutely difficult to handle for, especially for this nano positioning and reversal of direction with the nano positioning kind of a system. In focusing servo or in tracking servo also you may need to reverse in direction depend upon when the data is there on the surface of CD. And in scanner you can see that other multiple reflectors were used to reduce the image size and reduce the cost of the photo detector sensor.

Where you need such a large strip of photo detector sensor which is very expensive to produce in the first place. So, that can be reduced, the cost can be reduced by using this multiple photo detector effecter. So, these are the examples where you do something in the mechanical domain to ease out something in electronics domain. And many places you find that use of electronics itself will ease out lot of designs parts in the mechanical domain.

For lot of different examples as we saw in the engine case or say for example, ATM machine, there also we will find ease out the drudgery of counting the notes by a person, there are some mechanisms and some electronic systems that are used to count the notes. So, those are kind of examples we can think of.

(Refer Slide Time: 09:23)


And again coming back to the hard disc drive you have this arm for hard disc drive actuator and that is being designed to optimize for weight. So, let us get into little bit more of the thinking of why, what. So what is the shape of this arm and why? It is basically to reduce the weight wherever the stresses are having like higher values there only you need a material, where the stress values are very low or there is no stress, those parts of material can be removed.

And if you imagine when this arm moves very fast on the surface of the disc, what kind of forces are going to come on the arm, think about that. If you think carefully this is a circular motion for the arm and it is very fast motion, so one probably may not be able to ignore the centrifugal acceleration forces. So, the forces coming on the root of the arm because this is a mass which is getting thrown, or it has a tendency to throw out in the, by the acceleration of $\omega^2 r$.

So, any mass up here will have $\omega^2 r$ kind of a force coming up there. And that force is basically in the outward direction which is getting added up to the forces that acting in the root here. Or at ant section if a kind of cut the arm I will see that the mass which is beyond that cut will have tendency to get thrown away because of the high speed say, speed is $\omega$ for the arm.

Then, you can imagine that will have that force at, if you cut at different different sections here, as you cut the lower and lower sections here at the root towards the center of the rotation of the arm. The forces or amount of material that is beyond that cut will make it that the force coming on this cross sections are more and more towards root.

That is only we are talking about the centrifugal acceleration force and then because of this tangential acceleration of the mass which is moving will have some kind of a torque that is created here. So, those kind of forces are going to come on the arm and one can think about and make sure there arm is steady, arm should not give away to these forces and first of all fail in the stress, but other more important aspect many times is, this arm should not deflect more than what is required. Or more than some kind of a tolerance that can be allowed.

So, because arm deflection is what is going to cause lot of errors in system. So, this deformation of arm should not happen so much. So, many times we think that stress is what is a we have to design all the systems for. I mean if you see your mechanical elements design course, many times we talk about stress more than anything else in the design of mechanical elements.

So, they should not fail basically, but more than that like many systems would have this requirement that instead of failing, they should not deform more to disturb the operation. That is more rigor or more stronger constraint that is put which is more, which typically gives you the design which has much lesser stress than, what it cause a system to fail. So, keep in mind that, when we design the mechanical systems, they are design more for the deformation than for the stress.

(Refer Slide Time: 13:54)


So, we move forward and see this arm open often see more details about it. Now this more like a observation here. So, we can observe that, there is a coil up here and when the coil current is passed, the arm will get actuated.

Now, one can imagine that very easily that, look when the current is passed to this coil, by the virtue of the placement of this coil or the way the coil is designed, we see that this arm has a current in this direction, when the other arm has current in the opposite direction. So, if I look at this magnet what should be the profile of the magnate. In terms of its poles so that, see these are already, these are opposite direction for the current. So, if you imagine if this magnet has the entire top as a north pole, then the magnetic field is going to be in only one direction for both the sides.

And if that is the case then the forces that are getting applied on these coils are going to be equal and opposite direction. Considering that their filed has uniformity and then your arm is not going to move at all. So, the fact that the arm is designed to move means that on this magnet there should be, on one side there should be north pole and on the other side there should be the south pole and that is possible. So, other thing to observe that we will see this more in the detail, how one can observe this, see by looking at the magnet shape here you can see only part of the shape, the rest part is below this arm.

So, if you see carefully the shape of the magnate based on the shape one cannot make out that, where its poles are. So, how do you observe the poles that is a next question. So, we will see how to do that. And another thing that, there is a direct drive to this arm. So, this mechanical arm is not connected to some kind of a gear system here and or sector of the gear here, it is driven by a motor, or pinion which is attached to motor. That kind of a design is not there for the hard disk drive.

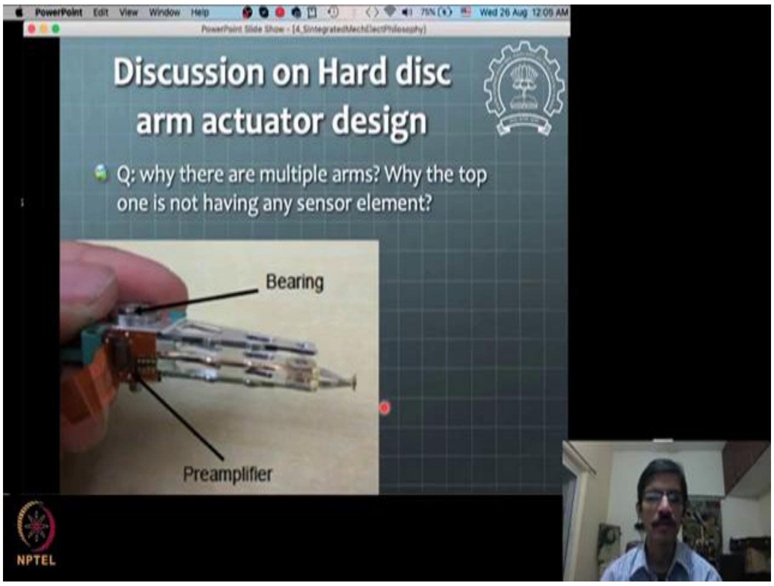
We do not want to introduce any friction and any, I would say any more friction, so there maybe some friction at this joint, this is revolute join, but it will have a bearing and that bearing will cause only some kind of a rolling friction rather than any sliding friction. We avoid the sliding friction by not attaching gear and the motor kind of a system and motor system also will be bulky here, and then one can imagine, okay, why not I attach motor itself here, on this joint.

It will be again like the direct drive for the motor, you need a bulky motor, typically if you see the motor specifications, the kind of torques that are needed versus speed. So, here the torque needed for getting this arm to move fast on the surface of the disc is relatively high and because of that you will need a high torque motor, which is going to be bulky. Typically motors are designed for, small motors will be having higher speeds and lesser torque. And that is where many times motor will always be used in conjunction with some kind of a gear transmission system.

So, in the CD-ROM drive we also saw the same thing was happening there. This is another working that we talked about just now. So, where are the poles on the magnet and why they are at those places. So, the reason for the poles, one south pole will be here and one north pole will be here. Because right now we want this coil always see a field which is opposite to the field that this coil be seeing so that the total force on the coil, which is produced by Lorentz force will be in one direction will not be opposing each other.

All right, then, yes, so next may be when we discuss this more, I may have some gadget to show you how do you can see the poles of magnets. We will try on some magnets. I do not know whether we will have this hard disc drive magnet itself available, but if at all that is available I will am showing that only.

(Refer Slide Time: 19:00)

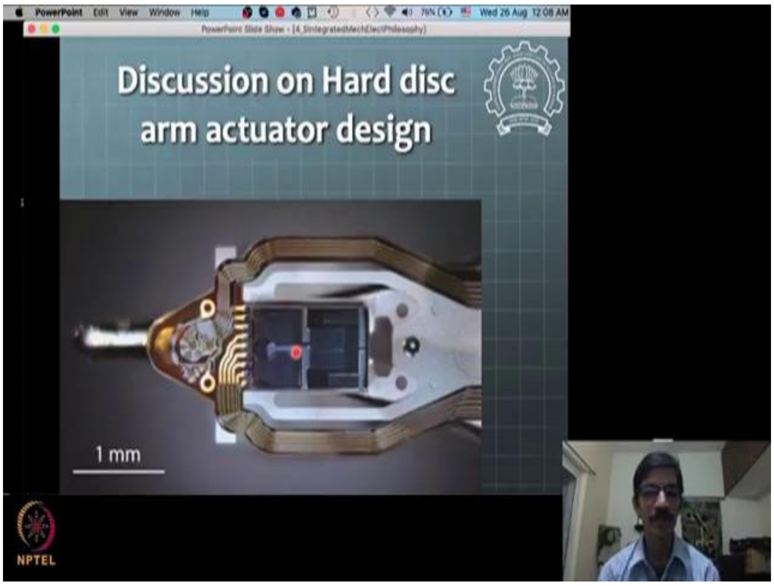



So, now we can see here like little more details. So, observe this carefully and see think what observations you can make, and then if you have any questions that you can ask about. So, think about some questions that you can ask, and then I will post these questions anyway, but you pause here for a while and think what kind of questions come to your mind, when you see this design.

So, what you observed here is, this is very thin arm up here, up here and up here, there are three levels in which, three layers in which you will have this arm put. And actually the reading is only in this part, this is some kind of a read head here, top side of the read head and bottom side of the read head. So, actually if you see this carefully this is some tweezers like thing which has to be opened up here and the disc will be inserted there, and then the head will be going on both the side, there will be one head on the top and one head on the bottom side.

So, why this design is there, and this arm, you see there is no head here at all. Why that is? So, these kind of questions you need to see and seek answers to these questions.

(Refer Slide Time: 20:31)



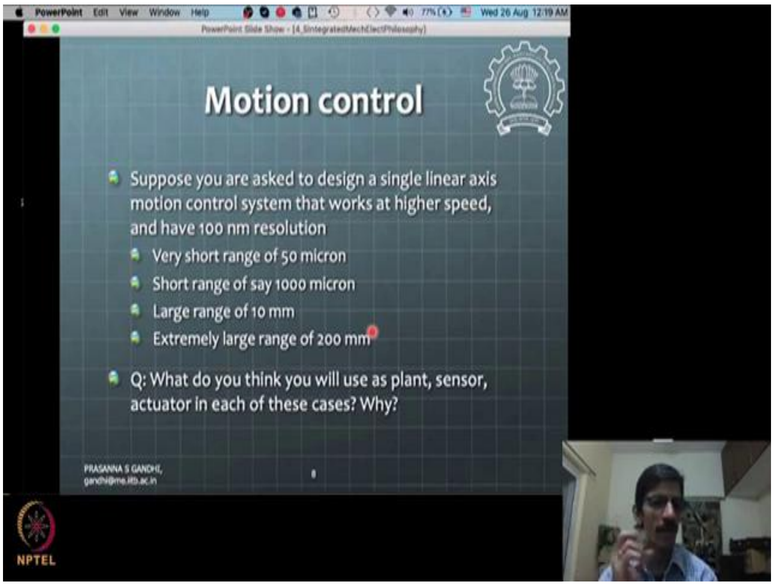

And then this is an actuator, disc actuator head, arm head here. And this head is actually the reading, there is some kind of magnetic sensors which are used to read the data on the surface of the disc. This is a magnified form of it, so this 1 mm you can see that small, very small tiny mechanism is there, and there is this flexure mechanism, compliant mechanism which is pressing the disc on the surface. This pressing the sensor not disc, the sensor on the surface of the disc.

Actually if you see then obvious question comes in the mind that, oh it seems in this figure you see that okay this is once I remove the disc from within they pinch each other, they are in pre-stress condition. That means when I put it on a disc surface this head is going to press on that surface of the disc. And then that press, would not it create any friction on the surface.

Why we want to press this on the surface of the disc? Can you think about that?  It may create a friction there, why we are creating this additional friction, is not it the counter-intuitive that okay we want to kind of have a magnetic reading happen with the absolutely no contact so that we do not have friction disturbing the positioning of the head on the surface of the disc.

So, this arm will have this unnecessary friction that may be coming up. Think about this and then it has something to do, with the interesting way in which this system actually works.

(Refer Slide Time: 22:46)




We move on now to the next generalization of this concept of these different designs. Such that they can be used now or this ideas or different concept that so far we have been looking at this existing mechatronic systems. How they can be little bit generalized for any motion control systems.

So typical, so for mechatronic engineer like the motion control is the base think to understand, we will take this as a base example case of development of some of these ideas and concepts, but they can be extended and applied in other domain of mechanical field. Say thermal domain or manufacturing or many other domains of mechanical phenomena that might be happening for which you may have electronic control to be exercised.

So, we will talk of motion control because this is one of the wider use in a mechatronics domain. Many system mechatronic systems we will find that they will have this motion, some motion thing getting controlled.

So, let say if you are asked this to get a design of single linear axis motion control system or mechatronic system that works at higher speed and has a 100 nanometer resolution. So, now we have a feel for what is 100 nanometer, you remember again we have talked about this while discussing this CD-ROM we have 1.6 micron spacing between the tracks of the CD. We need roughly this positioning accuracy.

So, suppose you are ask to design this, now obviously based on CD-ROM drive you can say that, okay, look for this kind of a thing I make go for compliant mechanisms, but are there any other ways of doing the same thing. So say if you are given that, okay I want it over very short range. So, if you see your CD-ROM typically may be roughly like a short range mechanism when we talk of compliant mechanism.

May be 1 mm, 2 mm kind of a motion, not even 2 mm maybe almost a 1 mm motion that may be happening in the CD-ROM head case for the compliant mechanism. So, only that means motion I want, I will go for compliant mechanism.

If I want much smaller range, still I can go for compliant mechanism, but there can be a option here of piezo’s, so piezo’s will have a very short range and that may get you the resolution better than 100 nanometer, many times like piezo’s resolution are much better than, they can be in the range of about 10 nanometer also possibility.

So, when you want very, very high resolution, but only over a very short range about 50 micron, 100 micron range. Then piezo’s are preferred as a actuator mechanism, and now we are talking in general of bigger size system. So, in some CD-ROM drive systems also people might have in the past tried out, I have never seen in piezo’s used in CD-ROM drive. There is a reason for that, but people might have tried that in the beginning to see the motion possibility with piezo’s to give you that much accuracy.

And one of the bigger disadvantage of piezo’s is that, see one good advantage is that they can be position better than 100 nanometer. And why that is happening if you see, carefully piezo’s typically require very high voltage when they are to be actuate it. So, the voltages are easily in the range of 50, 100 volts range and that might volt given and it deforms very very small even at that voltage based on their these different coefficient like d33, and those kind of piezo coefficients.

So, that small deformation is there with very high voltage, one can see that if I apply mili volts I am going to get the deformation to be much, much lesser in say some few nanometers accuracy. So, there from that perspective the piezo’s can be give a very robustly very small motions very easily.

So, just little bit of a common sense thinking one can do and say there, okay, look the resolution of the voltage that I can apply is may be 1 volt, 2 volt what kind of resolution I can apply. Or even mili volts is fair to apply, the noises are may be in a mili volts range, but I can go beyond 10, 20 mili volts, and you will not find the noise will be bothering you so much. So, piezo’s would be very good actuators for very, very small resolution and of course you need to pay more for the cost of the driving piezo’s.

You need to have a driver which is giving you this high voltages further piezo's to drive and they should not have very large range demand. So, if the actuator demands, okay I want to move over larger distances then piezo's may not be a good choice.

Nowadays also you will find there are something called inchworm motors. So, let me see if I can give you some kind of a flavor of that in, this inchworm motors may be may be we will give when we talk about the actuators maybe, maybe we can talk little more about. But basically these are multiple piezo's actuators together working in tandem in the sense that they will push something in a form of a wave.

So, may be the closest example I can give here is something like a centipede. Have you observed how centipede moves, that motion of the centipede with so many legs moving in tandem create some kind of a small wave as you see that centipede moving. You see some waves are going because the leg motions. And whose waves are actually if you imagine those are piezo's. So, the wave that piezo's are moved the motion takes place in that kind of a fashion.

And then one can enhance the range of piezo  actuators and there are actuators people have designed like that by using this kind of a inchworm motors, that is what they call it based on the worm kind of a motion.

The similar principle is used by mimicking of the similar principle is used. So, those are used for enhancing the range with piezo's. For moderate range 1 mm you can go for compliant mechanism designs, large range you can have for rack and pinion or screw driver kind of designs and extremely large range motion you can go for the belt drive systems. So, like that there are possibilities for different, different motion control systems.

And so one can say okay look I go for large range, if I go for large range, belt driver or some kind of a system and do it, will I get 100 nanometer resolution, oh no that is not possible to get. So you cannot just do this. So, large range we have seen also possibility of large range in the CD-ROM drive. So, CD surface you have to move larger distances 100 nanometer resolution. Only like the short range of up to 1,000 micron or  1 mm was taken care of by the compliant mechanism.

But, rest of the motion was coming actually by the rack and pinion kind of the drive. So you use some combination of rack and pinion belt drive or screw drive along with compliant mechanism. So, there will be 2 actuators here in this kind of a case, if you want to go really

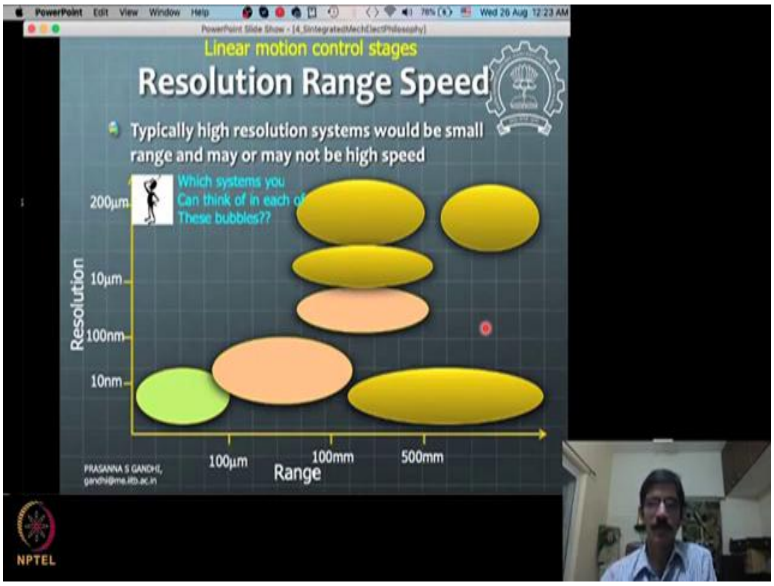
200 mm like a large motion and with the resolution of this 100 nanometers then you need to have a double actuator system.

So, 2 actuators are there or only 1 sensor will be there, 1 sensor will be looking at very high precision motion that is happening and then it will give a feedback to both of these systems in a interesting way about how to design control for that itself is a interesting control algorithm design problem or development problem.

So, that problem will be solved in the mathematical domain to implement control algorithm which can take care of a moving the, move the actuators in some kind of a coordination with each other such that you get this motion over the larger range also, and larger resolution also. Together that can be achieved. So, each of these things one can again categorize as okay what is a plant here, what are the sensors and actuators for different, different cases and things and why they are used?

This is another thought process one can get into and be able to appreciate what people have done in the design in this case.

(Refer Slide Time: 33:40)




So, based on that thinking one can come up with this filling of this chart of the range Vs resolution chart. And what are the actuators system some that you can see, or what are the control system or actuator sensor together which can put in these bubbles here. So, typically if you see range which is higher and resolution which is your, this domain is little difficult to obtain by a single actuator.

So, here we need 2 actuator design, but many other places, if we go linearly along this direction on this diagram then you will find that these are, it can be done with the single actuator; single sensor designs. So, also typically people may not be interested in these, where the range is very low which is coming almost a resolution itself. That thing I mean will not have requirement where the range is so low that it comes up almost close to the resolution requirement which is impossible for.

So, this is unfeasible or empty area, you will find no bubbles would be required up here. Would mainly system will be centered around this, most of the systems will be centered around this, and some special systems will require very high resolution and high range. Typically, combination of high resolution and high range will be very small number of applications.

So, in the natural also if you see, something which is happening at a larger range that will be hardly, the resolution of those things will be low. If you see the systems you developed also mechanical systems developed for example, the crane system, that transports material from one place to other place for the building constriction or some of the kind of applications, there also you see that the positioning resolution or resolution of the placement of the object will be much lesser, much coarser than for smallest system say some CD-ROM drive system or that is extremely small.

But, you can see through that wherever there is a high resolution requirement typically the ranges are going to be small, and wherever there is a larger ranges, the resolution also will be little coarse there. Requirement also will be little coarsed. Typically we will move along some kind of one axis up here, central axis here.

And there are some special systems only that will be having this kind of requirement of both together. And this is interesting area, I mean nowadays with the advances in the nano technology and micro technology this area is getting now more and more explored for interesting research applications there.

So, we move on to the next slide. So, you pause here and think how we can fill in each bubble and you have your own filling done here on the paper. This will be, this kind of a thought process will be very interesting to open up some of the concepts in your mind. Even if you go wrong do not worry about, let it be whatever you think, whatever comes to your mind, that will raise some kind of questions later and when they are clarified you will have some conceptual understanding that will be happening here.