Design of Mechatronic Systems
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Lecture 32
Selection of Sensors and Actuators – Part II

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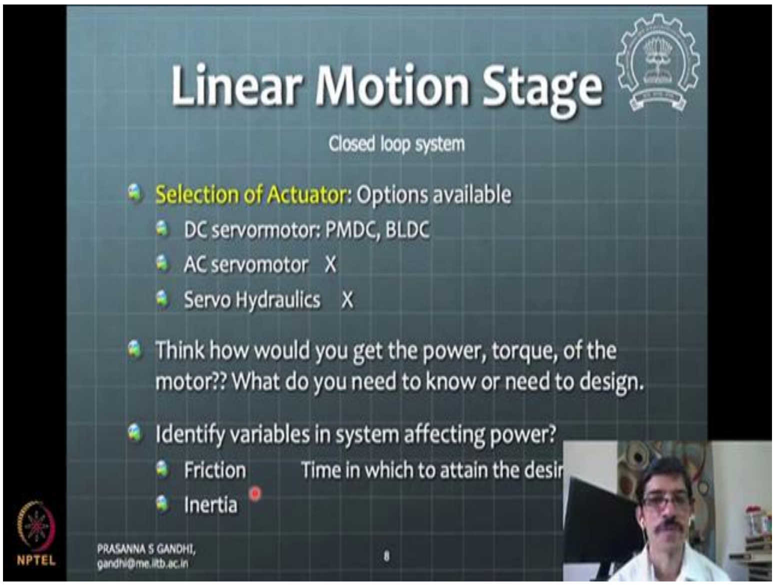

Then we go for actuator selection, to discuss actuator selection, typically, we have these different choices available, you look at different options available and then like make a choice based on that. Now, when we have a positioning requirement, then BLDC motors typically are not used. We will use permanent magnet DC motors or you have also stepper motors here. So, but we are talking about servo. So, in servo, stepper motors are not a servo kind of a drive, they are more like open loop kind of a drive.

So, but depending upon application you may do the choice actually. Here, we are required to do like servo operation by using some closed loop feedback. That is why, we are kind of like constraint to kind of using permanent magnet DC motors. That is a choice that we will typically carry out. And then now, the question is how do you get power and torque for this motor. And then for, this again one can see that, if we estimate now like the mass in the system and forces that are coming, then we will be able to kind of get to the torque.

Now, how do you get the forces, what are the forces can you think about, for this linear stage motion when we want to move in by say 20 mm per second kind of a speed. See, this is not very, so we can say friction force of course that is there, but how do you get to know what is force coming because of the inertia, moving elements or moving masses in a system. This is little kind of a tricky to estimate. So, for that you need to know what is acceleration, which we have not specified in the problem.

So, we have specified, I want to kind of go with the range of 60 mm and then like, so that is where like we need to get estimates of acceleration. So, I will tell you how do we get the estimate of acceleration. And once you have an estimate of acceleration, then mass into acceleration will be the force and that force times velocity will lead you to the power in the system.

So, there are this friction, is what one element in the system that will affect the power and inertia is another element that will affect the power. So, friction estimation, you should have some kind of a ballpark figure estimates of the friction and that, for that you can use the tables online you will find some information about coefficient of friction between the two surfaces in presence of some lubrication or not lubrication. All those kinds of things we will use, make use of that, see what are the normal reactions typically from your applications coming on the system and then you can estimate μ times n like friction force and friction torque.

So, many times this friction is much higher consideration than inertia especially for the slow motion systems and systems which are having this kind of spring-loaded stuff. So, that is why, so enhanced accuracy one has to, so you can see that this enhancement in accuracy or backlash consideration that comes at a cost of pennies, like what cost you pay is like extra power that you have to get into system to work on this additional friction that will happen because of the spring loading of two elements.

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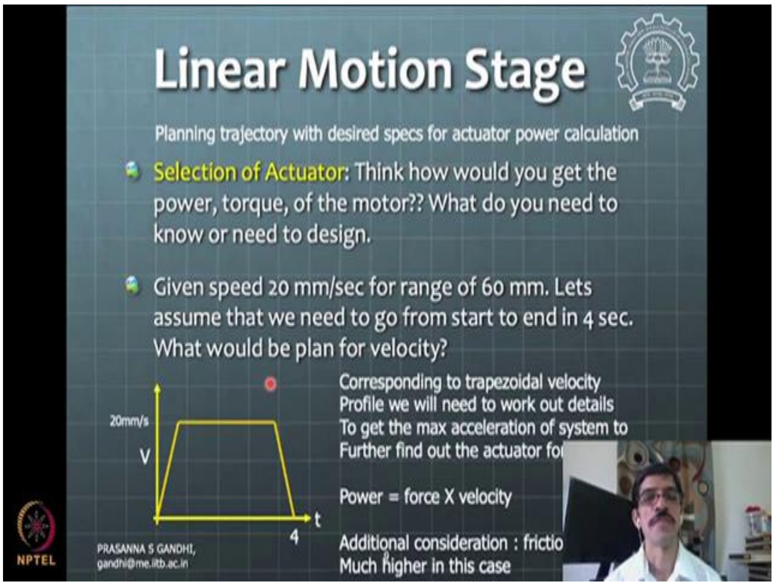

So, this is an important thing now, we need to kind of plan a trajectory for getting this estimation of power. So, we are on this question, how do you estimate power? And as I said, like given the speed of 20 mm range of 60 mm, 20 mm per second for the range of 60 mm, we have to assume something, now to kind of get to the acceleration. We are not given directly any acceleration in the system. So, how do you do that?

We say we need to go from start to end in say 4 seconds or this is one can, we can ask the application user who, what is like how much roughly the duration in which you would go, like to go from one place to another place. So, this is somewhat important, such that 20 mm per second we go 16 mm like but, we do not know how soon we should get to 20 mm. So, we cannot just directly jump from start to like 20 mm. We need to have some acceleration to go to 20 mm per second kind of a speed.

So, we go, let us say, we go to start to end from in 4 seconds. So, we can kind of, do some kind of estimation, see this is taking 3 seconds to go from like start to end with 20 mm per second speed. So, we want to do this operation say roughly, in 3 seconds with acceleration or 4 seconds with acceleration. So, one can kind of like see that number will be not too far from these 3 seconds. So, we can plan, we can make some kind of assumptions of this sort and then plan our trajectory for velocity.

So, now, if I want to go now, say let us say I have chosen this 4 seconds or some *t* whatever seconds time I have chosen and I want to kind of get, limit my maximum velocity to 20 mm per second, then I can shape, like what are these straight line rise that will give me the acceleration to go from 0 to 20 mm per second speed, how much should be this duration, when

I like complete my task in 4 seconds with this distillation also for the same time duration as the acceleration time duration, then I reached this 60 mm.

So, one can make such kind of assumption and proceed for getting the acceleration. Once you have acceleration, one can get to the force is equal to mass into acceleration. So, that is the maximum acceleration, maximum force that your system will see. Although during the range of this 20 mm constant speed, there is no force other than the friction force that would be seen. There was no inertia force will appear, because you are now moving at constant speed. So, these are the kind of sense or these are kind of a feel, of how one can, one has to kind of think and get to the estimates of power.

So, this is a power which is corresponding to inertia and then we can estimate the power corresponding to friction losses and then we can get the total power in the system. So, this is a typical kind of exercise one would do for any mechatronic system, selection of sensors and actuators.

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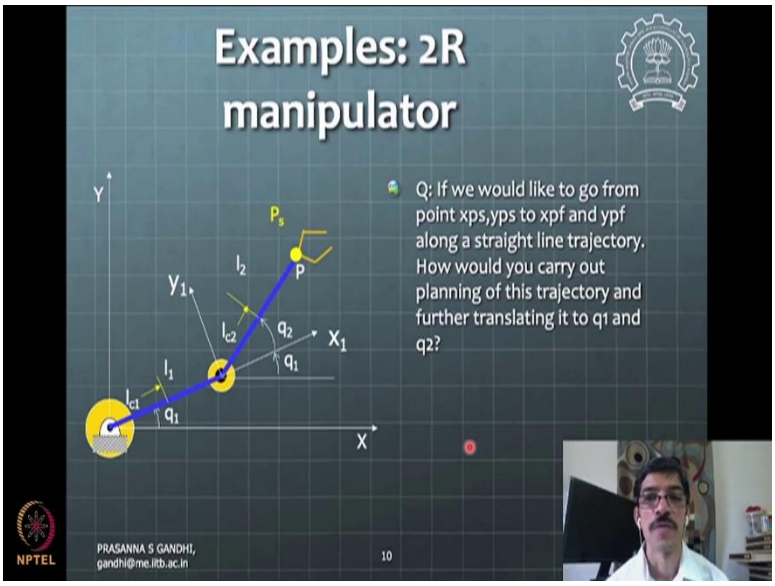

So, now, let us see this with the example of 2-R manipulator a little bit more, because there are some kinds of variations that will happen here, because the kinematic relationships would be different. So, we will talk briefly about that and then we will close this chapter. So, now, this is the 2-R manipulator, that you have done modeling for. And if, this is a problem that is given to you that we like to go from point say starting point p_s to some end point p_f along a straight-line trajectory. That is what is our aim for this. Some kind of a straight line I have to kind of go along.

So, how do I carry out planning of this trajectory and then get further estimates of the sensor resolution. So, I am given, that I have to go by the straight-line trajectory for some kind of assembly line operation and or some kind of operation. And I am given, that I have been, while on the trajectory I can be off the trajectory by some δ amount. So, that is what is given as a user specification which needs to be translated into sensor specification eventually.

So, I want to go along this trajectory and I cannot be off the trajectory more than some $\pm\delta$ amount, and then how do I kind of go about getting the sensor and actuator specifications. So, you assume some kind of inertia for these elements and things like that.

So, this will be typically iterative process to designing the manipulator itself, like it will be quite a few parameters that are going to be unknown to begin with. And so, you start off with assuming some kind of a ballpark figure values or some kind of, you keep them as a variable and then you keep on kind of simulating and changing.

So, typically what you will do is for such an iterative process, is to create some kind of excel sheets in which like you gain these, some of these parameters as input to the input block of the excel part and then you estimate some outputs and then like you see those numbers and based on the numbers you start modifying the inputs to kind of get to like what specification that you would like to achieve further. So, that is one of the ways one can do nicely.

So, making use of the excel sheets to do these kind of design calculations little bit iteratively. And you might have seen in your normal mechanical design process also, those kind of excel sheets nowadays are available from many vendors or some of the manufacturers catalogs.

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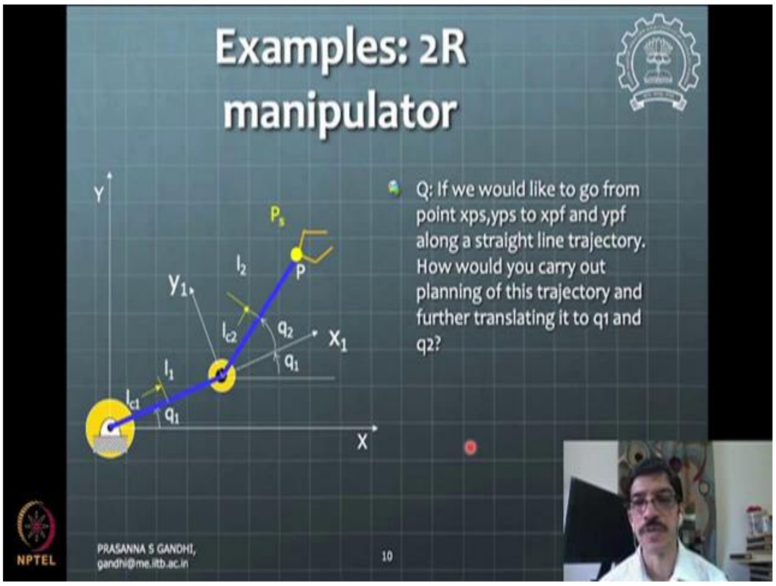

So, this is our job to estimate now like going from this to this. So, first thing we should, we will do is like we should, so the crux of this all is how do you plan the trajectory. So, as we saw in the last example also, once we plan a trajectory, lot of things will estimate and will get clear. So, now how do you plan for such a trajectory?

So, now, say let us assume that, I want to go from this initial position to final position in some time *t* or in some say 5 seconds or something like that, then how do I kind of plan my trajectories. So, can you think of what is, what comes to your mind at this point? Just put it on paper and then let us move on.

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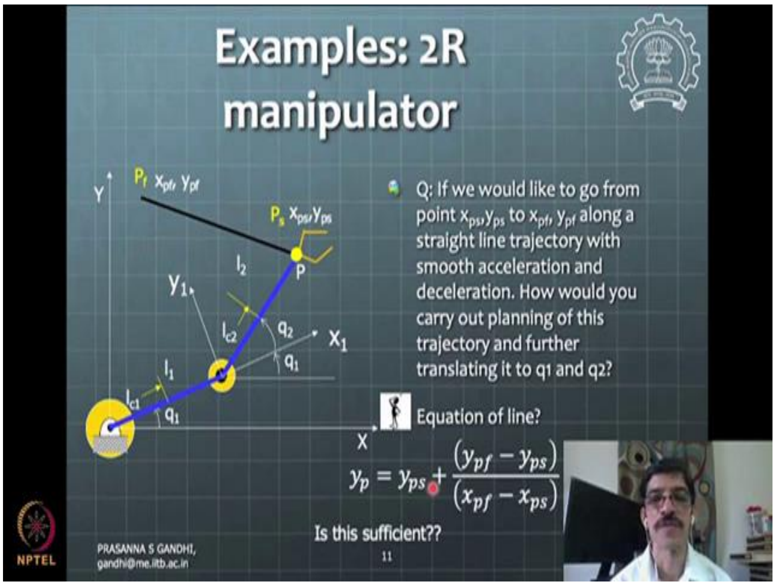

So, for this kind of a trajectory what is, first I need to kind of get some equations for this straight line. So, we will get the equation of a line first, say starting from point, so from your basics of geometry like you can write this equation. Not a bit problem. So, you are, if you are given x_p as a position, then corresponding to that if I want to be on the straight line a y_p position will be given by this equation. Given first like starting point and end point I am having this kind of a relationship to go if I know x_p. But I do not know x_p, is not sufficient.

How do I plan now? Now, what is a thing is to plan for x_p now, then my y_p plan will be coming out of this relationship. So, I need to plan for, how my trajectory for x_p will evolve in time. So, we may say, so can you think about how do you plan for now x_p variable. What is your desired x_p variable? So, that I go from like this point to this point in say some time t for 5 seconds say for example. In 5 seconds, I want to go from this point to this point. And I know this coordinates and other stuff. So, how do I plan for this kind of trajectory?

So, then I say from x_p perspective, again from these x value here, x_{ps} value to x_{pf} value here, now this would be x value here, I will need to go in say in 5 seconds. So, if I know these, then like I can plan for this x part alone to begin with and y part will be estimated from this.

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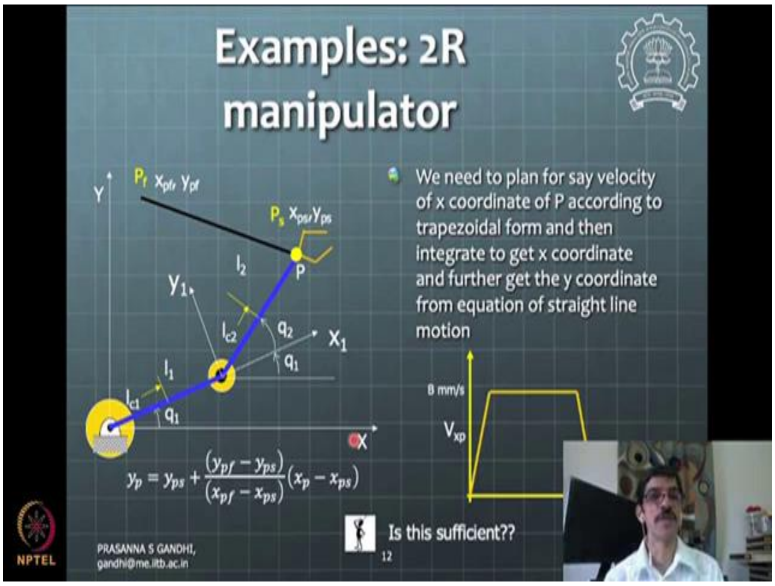

So, now, I can do this. We can, I can plan say, some velocity say B mm/second kind of a velocity, I will achieve during my motion path and then I go again trapezoidal kind of form of a velocity. So, in say t is 5 seconds now, in 5 seconds I want to go via this kind of a profile of velocity.

And I have under constraint that, so I again assume that, this is say time t_1 and then this is also like total time from here to here is t_1 so that we are accelerating and decelerating in the same time and with that, I would estimate what is displacement that would happen and that displacement should match to my x motion which is x_{ps} - x_{pf}. So, that is total x motion that should happen.

So, I will plan this velocity profile first, and then like I will estimate what is the acceleration or like what is the speed, number. I can choose to kind of achieve the final displacement. Once I know this, I will get y coordinate from the equation, that I have seen in the previous slide. So, is this again sufficient?

No, you can see that this is not yet sufficient, because I just know now my x desired and y desired values for this point P, but they need to get translated to these q_1 and q_2. So, for that you need to recall your kinematic relationships. So, you plan first your x desired value, y desired value and now come to kinematic relationships to get q_1 and q_2 desired values.

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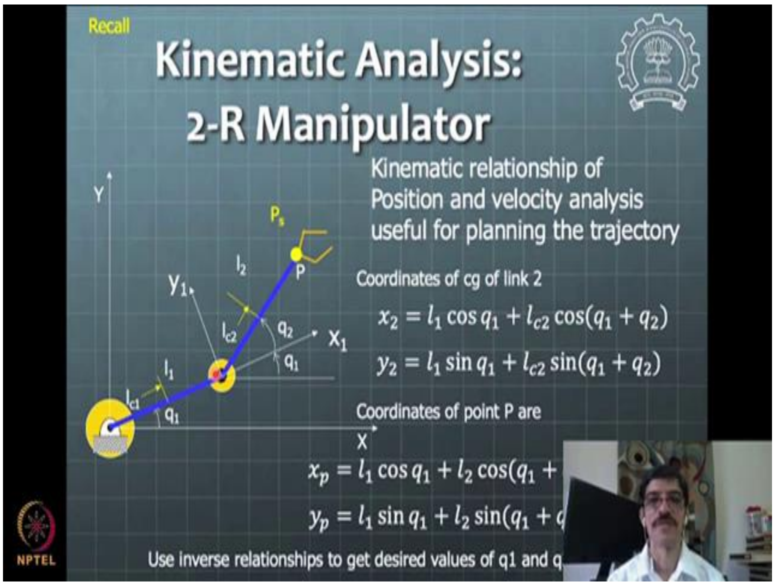

So, this is how like you recall your, so you recall that coordinates of CG of link 2, where this much this and now, if you change this l_{c2} to l_2 then like that becomes coordinates of point P. Use this inverse of this relationship, to get to the values of q_1 and q_2. So, you see that, typically these relationships are not linear. They have some kind of a non-linearity in them and that will have some kind of implications.

So, for example, for given x_p and y_p, there will be two possibilities for q_1 and q_2 solutions. One is on the side, you can see and other solution will be on the other side, like the link going like that and like coming in like that, a symmetric about a straight line going from the origin to the point *P*, the symmetric solution of that let us say.

So, one has to consider, like that part in doing the inverse computation so that you do not suddenly kind of go for some of the positions on the other side and some positions on one side and then you will have a trouble in executing that kind of a trajectory. So, from x_p and y_p you get to q_1 and q_2 now as a plan trajectories.

Once you have these planned trajectories available, one can see now if there is a δ change in the resolution of q_1 or q_2, how much will be the change or like deviation from the straight line that is going to happen. And now one can see, it is not very difficult to see that if I go the same straight line here, or at some other point in the workspace, these relationships are going to change. So, there are like, some more considerations that will happen on the way.

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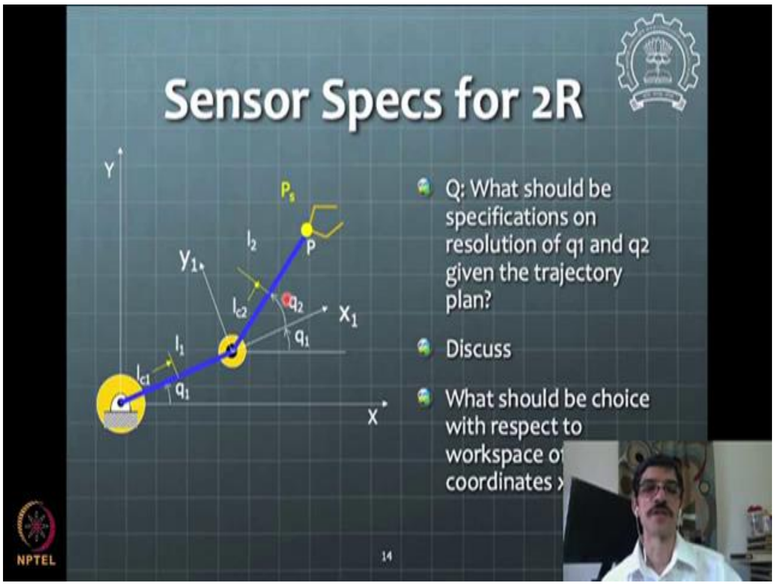

So, what are the resolutions on q_1 and q_2 so given this kind of a trajectory plan? So, I want to go to final position P_f within, say some accuracy say 10-micron, 15 micron whatever micron accuracy, then correspondingly what is q_1 and q_2 the solutions, that I will need to have so that is another kind of questions that we will need to think about.

So, we will discuss little bit more in the, in our discussion part again. But these are the things one need to think about. See given specifications on the resolution on q_1 and q_2, how do you kind of get to the deviation on the, from the straight-line path or reverse kind of a problem, inverse problem.

So, based on that one can take a call on what is the resolution that is required on the sensors. And then, one can also see that if I choose this P_s coordinate starting point at some different locations, say it is more closer to the origin or this motor, then the kind of variation I would get for q_1 and q_2, would be different than range of motion that we will get for q_1 and q_2 will be different from if I start from some other point. So, were to choose this starting point from, if you have a choice. If you are given some kind of choice for the starting point, where you will choose it from?

Those are kind of thinking that you will need to do. And for that it is not very trivial thing. It has to, one has to kind of do some simulations and see the workspace of this manipulator and see, which are the good areas in the workspace to have this operation done. Typically, one of the considerations is that, if you are like very close to the straight-line position, singular position that we have talked about, when q_1 and q_2 are, q_2 is 0, so only q_1 is there, q_2 is 0, then this is a straight-line path.

And suppose, now if I choose point P_s at the end of that path, I do not have like I cannot draw the straight line very easily. I have to get out of this singular position, and then maybe I will be able to kind of move along the straight line which is inside the workspace. So, this notion of workspace of this motion of point P, workspace is basically all the set of points P which can be reachable by whatever the link lengths that are given here and for whatever angles for q_1 and q_2 considering, they can move total 360° possibility. So, those are kind of considerations, that one would need to give for sensor specifications.

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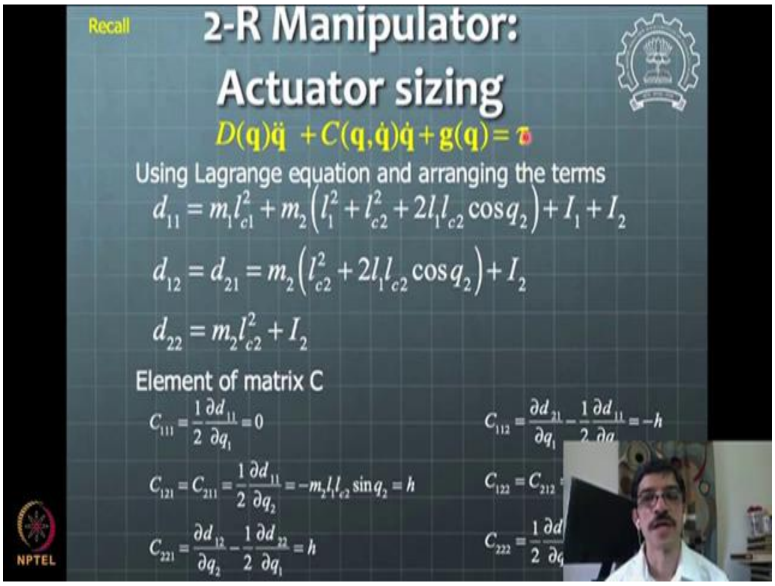

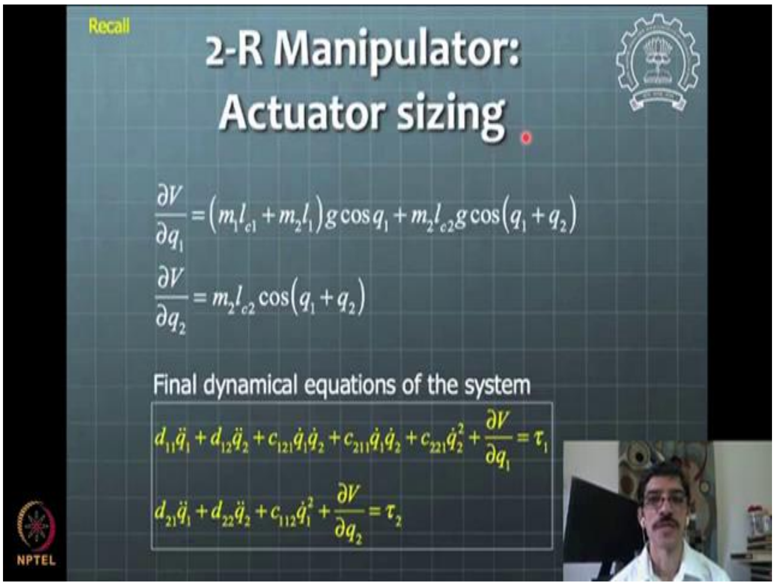
Recall
2-R Manipulator:
Actuator sizing
$\frac{\partial V}{\partial q_1} = (m_1 l_{c1} + m_2 l_1) g \cos q_1 + m_2 l_{c2} g \cos(q_1 + q_2)$
$\frac{\partial V}{\partial q_2} = m_2 l_{c2} \cos(q_1 + q_2)$
Final dynamical equations of the system
$d_{11}\ddot{q}_1 + d_{12}\ddot{q}_2 + c_{121}\dot{q}_1\dot{q}_2 + c_{211}\dot{q}_1\dot{q}_2 + c_{221}\dot{q}_2^2 + \frac{\partial V}{\partial q_1} = \tau_1$
$d_{21}\ddot{q}_1 + d_{22}\ddot{q}_2 + c_{112}\dot{q}_1^2 + \frac{\partial V}{\partial q_2} = \tau_2$
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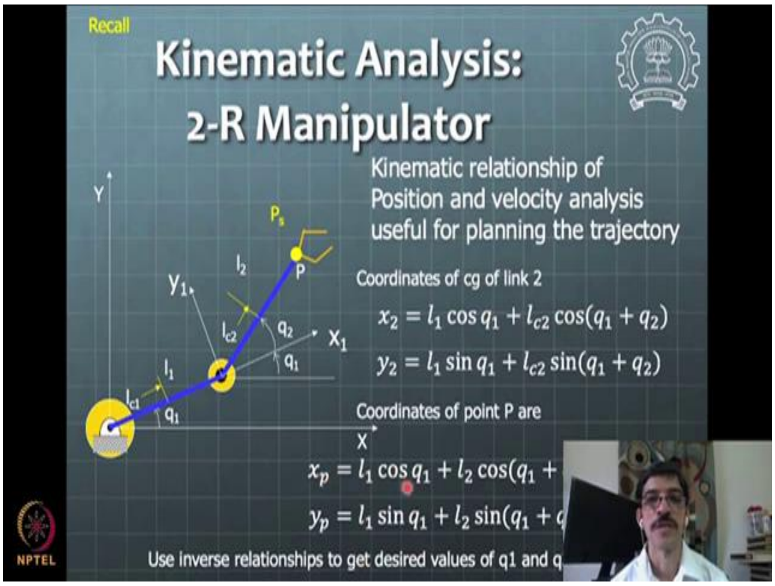
Recall
Kinematic Analysis:
2-R Manipulator
Kinematic relationship of
Position and velocity analysis
useful for planning the trajectory
Coordinates of cg of link 2
$x_2 = l_1 \cos q_1 + l_{c2} \cos(q_1 + q_2)$
$y_2 = l_1 \sin q_1 + l_{c2} \sin(q_1 + q_2)$
Coordinates of point P are
$x_p = l_1 \cos q_1 + l_2 \cos(q_1 +$
$y_p = l_1 \sin q_1 + l_2 \sin(q_1 + q$
Use inverse relationships to get desired values of q1 and q
Y
X
P_s
P
Y_1
X_1
l_1
l_2
l_{c1}
l_{c2}
q_1
q_2
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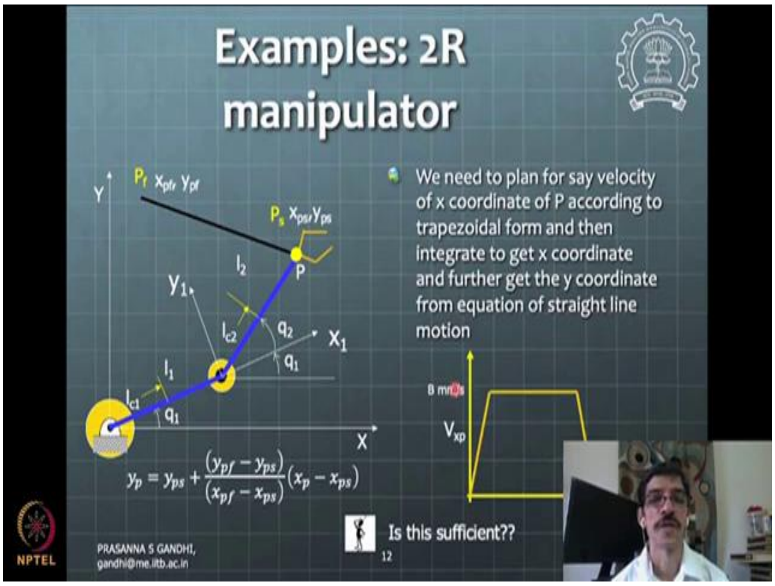
Examples: 2R
manipulator
We need to plan for say velocity of x coordinate of P according to trapezoidal form and then integrate to get x coordinate and further get the y coordinate from equation of straight line motion
P_f x_{pf}, y_{pf}
P_s x_{ps}, y_{ps}
Y
X
P
Y_1
X_1
l_1
l_2
l_{c1}
l_{c2}
q_1
q_2
V_{xp}
$y_p = y_{ps} + \frac{(y_{pf} - y_{ps})}{(x_{pf} - x_{ps})}(x_p - x_{ps})$
Is this sufficient??
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And when you come to actuator sizing, we need to go back to this modeling part, to some extent. If at all we want to get into, you remember this model that we have derived for the 2-R manipulator. So, from this plan of q_1 and q_2, trajectories one can get to know this is, say suppose this is $\ddot{q}$ and $\dot{q}$ all these things are desired values then I can get what directly the torque which is required to kind of achieve that. So, that is based on only like inertial torques. Friction needs consider in this equation yet.

So, if it is in a vertical plane, this gravity component will be dominant. And the inertia component depending upon how fast we want to kind of go, the inertia components may be dominant. So, both *C* and *D* are kind of inertial terms in the system. So, I will substitute these desired trajectories in here, to get estimate of like the torque is one way of doing things or one can kind of say that in a similar manner that we have seen what is the maximum torque that is, maximum acceleration that is coming into the system and estimating like more kind of conservative forces, estimations of the force is coming.

And see now, these matrices or inertia terms are dependent upon *q* in general. So, where you will choose to move that starting point P_s, you will have lot of variations that could be possible in terms of Dq matrix and correspondingly like your estimates of the inertial torques. So, once you have estimated like some kind of a torque here, you can kind of consider that.

So, this is like coming as a τ_1 and τ_2 torque first motor and the second motor then you, so by substituting like your desired trajectories, then you use that with the velocity to torque into velocity as a power estimation for the motor. And this torque will give you like maximum torque along the trajectory where it is happening, and based on that you can add some factor of safety and you can add friction also to estimate some kind of a torque for your motors in respective joints.

So, this is about sizing the actuator in the same kind of fashion as we did for the case of. So, all these actuator sizing considerations, will need to plan a territory, that is the bottom line here. You need to plan this trajectory to kind of get to this. So, for example, here we had just said this q_1 and q_2 will be obtained based on this plan for x_p to move along the straight line.

This is the kind of, so you will have similar kind of a diagram for q_1 and q_2 again. So, planning the territory is an important step in many- many mechatronic systems I would say. For whatever kind of motion that you would like to carry out, you will need to have this kind of motion plan to get good estimates of the specifications. So, that is what is a bottom line.

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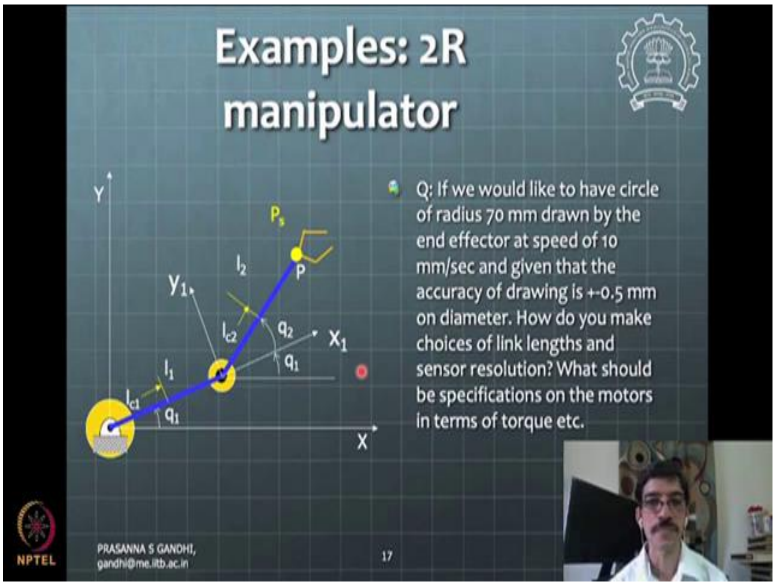

And now I would suggest, like you think about this problem. Suppose you want to draw circle, instead of just moving along a straight line, I would like to draw a circle here. And I have given some accuracy and some speed of drawing circle. So, speed of 10 mm per second is what I have been given.

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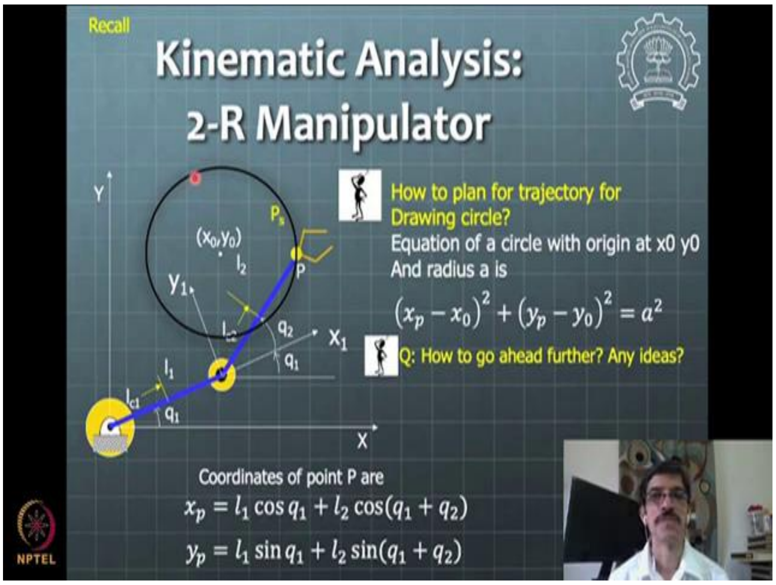

So, the end effecter here should be moving along this circle by a speed of 10 mm per second. Then in that case, how would you plan this trajectory is a question. So, this circle equation something will be given, then how do you kind of plan now the further thing? So, you think about this issue that I want to move my velocity along the circle should be 10 mm per second

How can I plan such a kind of trajectory? So, think about it. So, is this a right choice for the coordinate system for the planning or not? Think about that.

So, I will stop here. We will see if there are any, we will take up this again if it all needs to be in the discussion class part. So, this is how like you can make this kind of concept generalized. So, from these two examples, first we have seen like a linear stage which is single degree of freedom kind of a case, now this is 2-R manipulator, two degree of freedom case, this can be now generalized to n degree of freedom kind of a system to think about.

So, for that, you will need your equations of motion in place typically. Otherwise, you will get too much into, two conservative estimates might be happening. If you do not really do the modeling completely, then your estimates, you can still kind of new actuators which are now, they can function, but they are like maybe too far more than what is required. So, I think we will stop here.