NPTEL Online Certification Courses

COLLABORATIVE ROBOTS (COBOTS): THEORY AND PRACTICE

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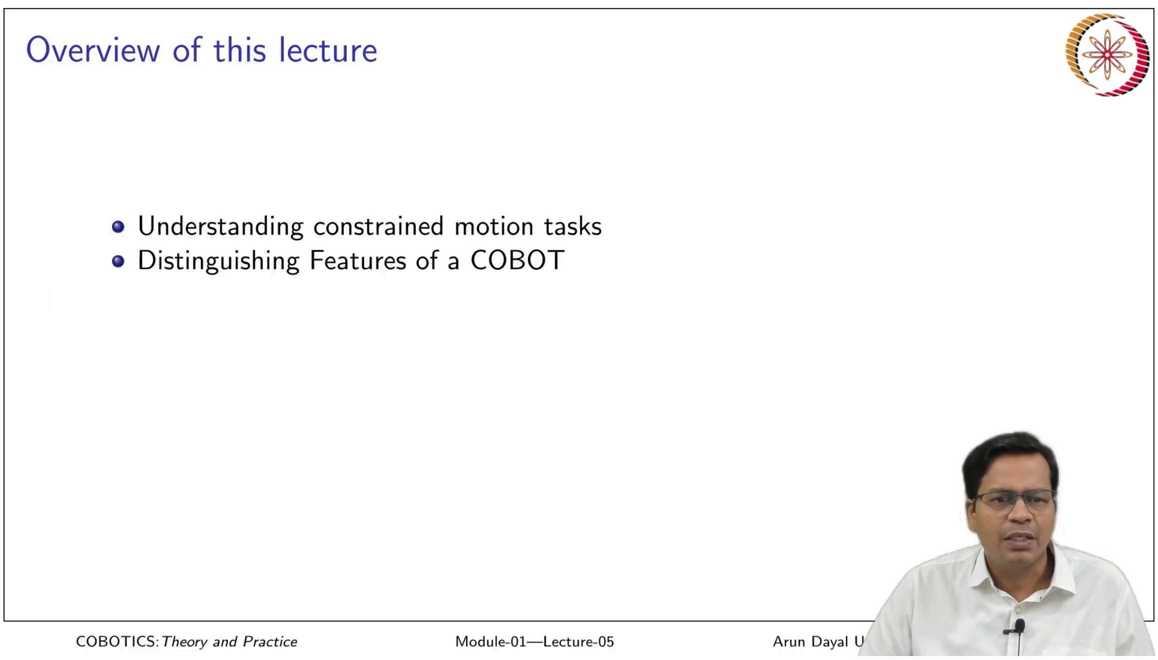
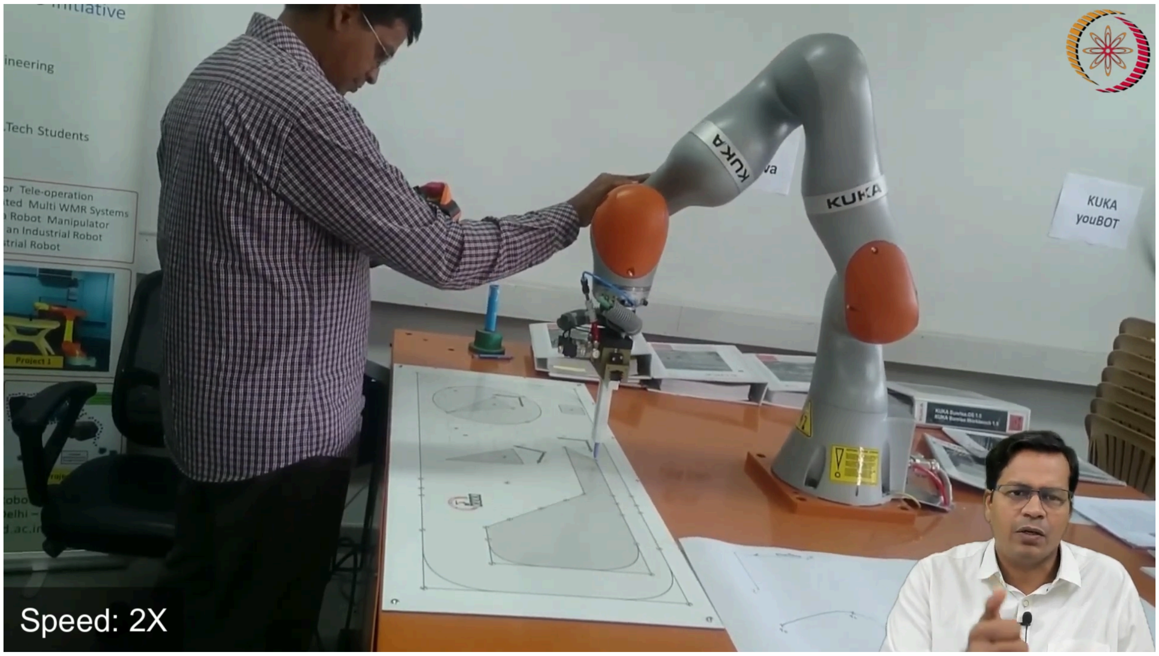
Week: 01
Lecture: 05

Constrained Motion Task and Distinguishing Features of a COBOT

Welcome back. In the last lecture, I discussed the fundamental technological difference between a Cobot and a traditional industrial robot and how it has advanced over the years. I discussed the design of the joint actuator, the controller, the arm, and the overall system.

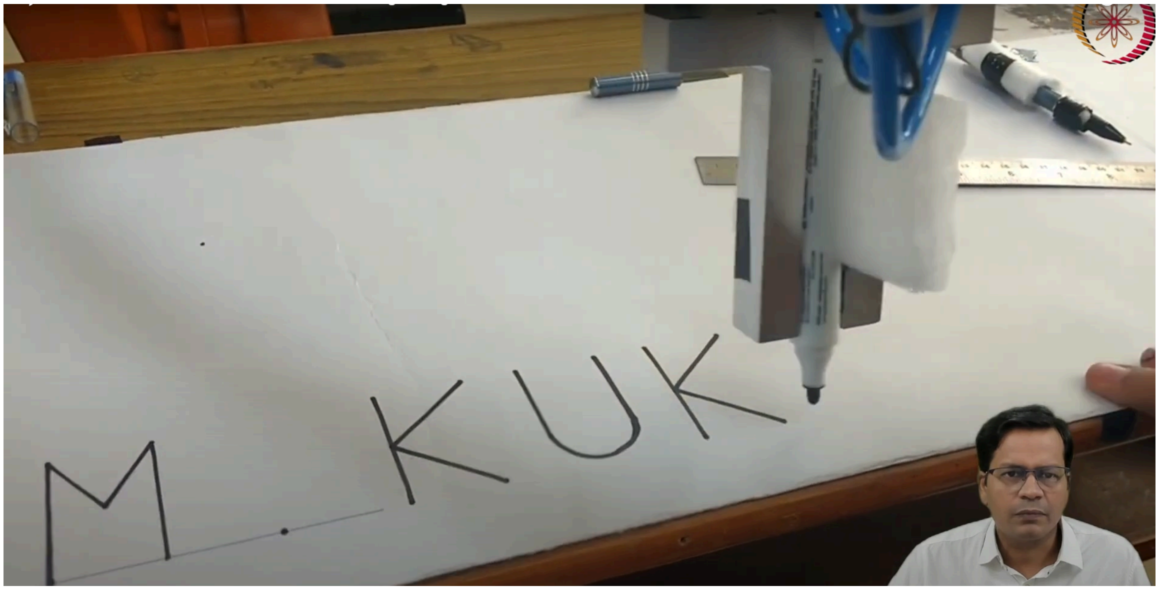


So, in this lecture, I will discuss the fundamentals of its implementation, that is, the constrained motion task and the distinguishing features of a Cobot that we look for when we use a Cobot. Let us first have a look at the lead-through programming that we have heard of quite often that a Cobot possesses. You can take it to any point; you can teach it instead of jogging it to a location and teaching it. So, this is something very innovative that has come with the Cobot.

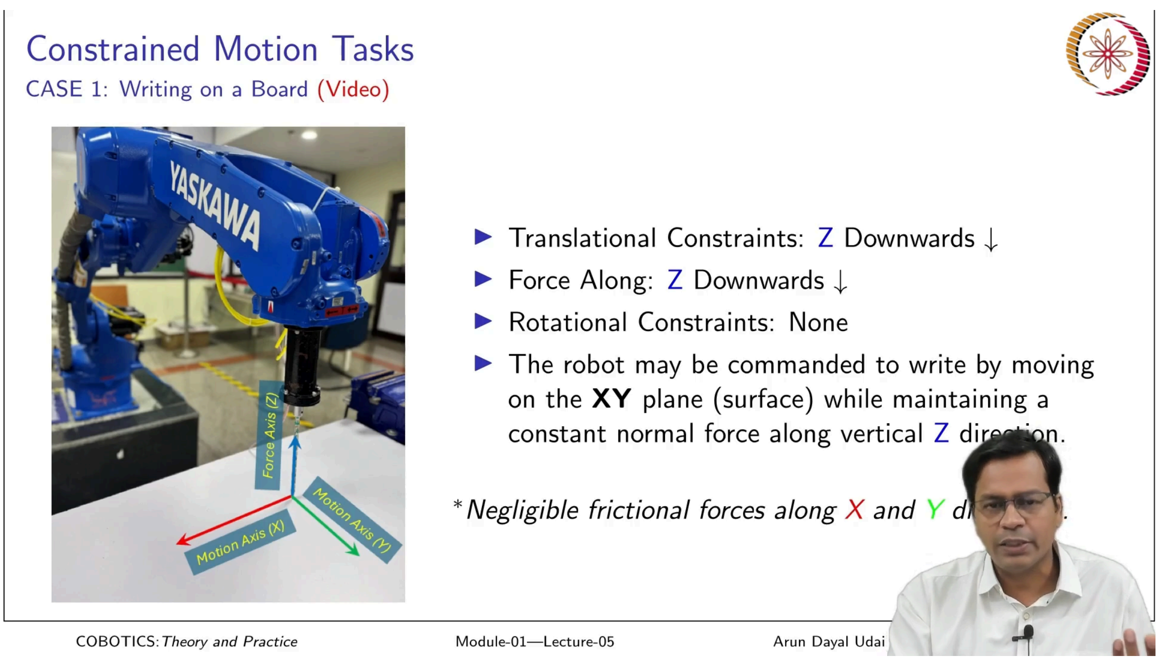


Let us have a look at that. You see what I am doing; I am taking the robot to different points on a trajectory and I am teaching those points while I am dragging the robot manually, through my hand only. I am able to drag it. This robot is so soft; it allows me to do that. Every point I take it to, I am teaching it, taking it, teaching it. So, I am not required to take it through my teach pendants. I am not jogging it manually. I can directly take my arm, and that arm is quite soft.

Once it is completely trained, what will I do? I will just press a repeat button. So, whatever points I have taught it will quickly follow them. This is one very good feature that is normally present in a Cobot because it is back-drivable, compliant, and fully gravity-compensated. So, it is very easy to do that. So, this is one of the very good features that is present in a Cobot.



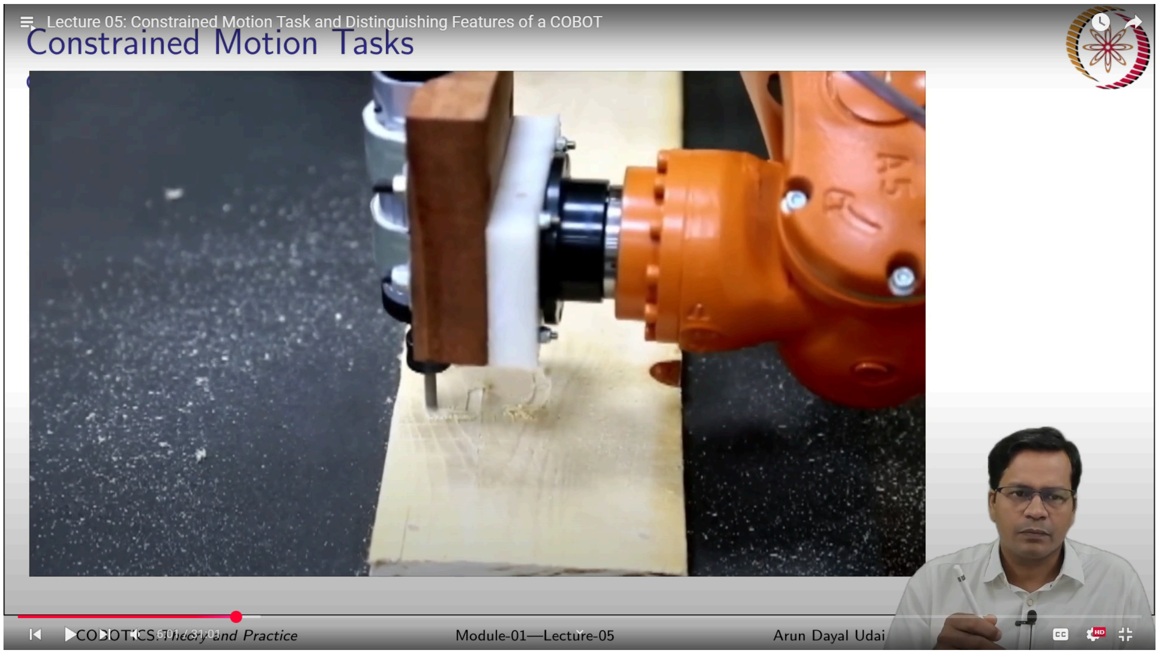
So, let us continue with understanding the constrained motion task. The first one is writing on a board. So, when we write on a board, what are all the things that go into it? You see, what is happening is the robot is able to write on a board that is placed horizontally on the table.



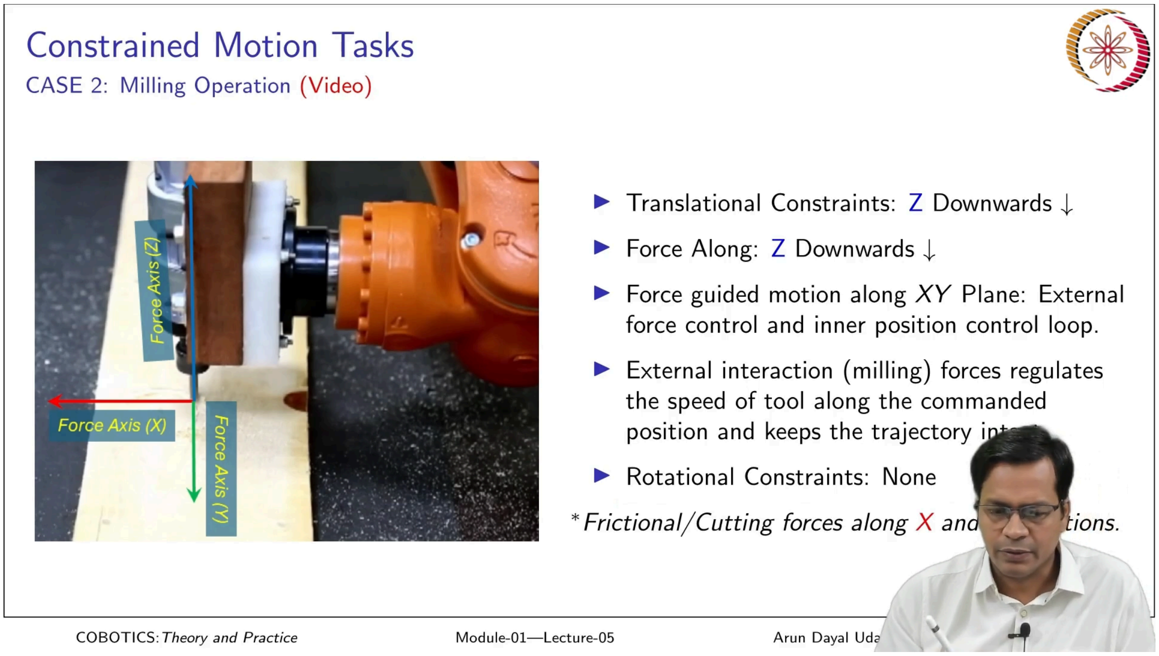
The situation is very much like this: when you have a motion axis along the plane, I can move the robot along the plane, and there is a point of contact that is happening somewhere over here. So, what are the constraints which are present? There exists a translational constraint, that is, the downward Z-direction; I cannot make the robot go into the board. So, actually, it can remain on the board, and there has to be a constant normal force that is to be maintained while I do all the writing processes. So, the force along the Z Downward direction is only allowed. If you take the force along the vertical upward direction, it will lose its contact, and no more writing will happen. So, you have to continuously maintain the normal force against the surface. And because there is almost negligible friction along the surface, you are free to move along the x and y directions.

So, there are also no rotational constraints. It can rotate about any of these axes. It can roll, it can pitch, and it can rotate about its own axis. So, there are no rotational constraints here. But yes, once it has established its contact using the robot, this orientation change is not very much required.

So, the robot may be commanded to write by moving on the XY plane, which is the surface, while maintaining a constant new reaction force along the vertical z direction. Essentially, you can produce force only when motion is constrained. A robot which is free to move in the air cannot generate any force at its end effector. Got it? So, in whichever direction out of the six directions—three for translation, three for orientation—whichever is constrained, you can generate force or moment accordingly in that particular direction. So, that is the philosophy here. So, this is how the writing happens when we do it. It is done using a robot. So, negligible friction is present along the X and Y directions.



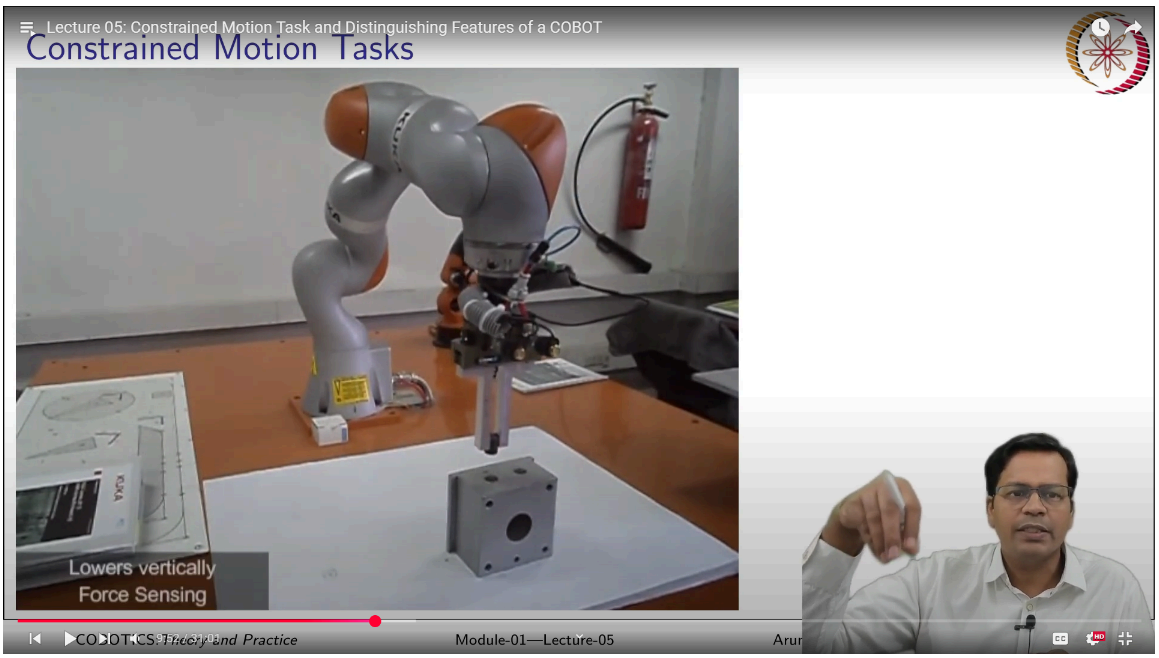
So, the next one is the case of milling. So, let me show the video once again here. So, this is a milling operation where the robot is taken to one end of the board, which is a wooden board with a pneumatic drilling machine, and you have an end mill fitted there. So, again, it tracks the entire trajectory, removing material along the XY plane, which is the plane of the plank here. You see, it moves across the surface and finally completes the task. So, once it is completed, it takes up the tool. So, reaching that point and going back is essentially a position control task. So, it is a position control trajectory using a standard robot, but maintaining contact and doing this work requires some compliance in action. That is what is realised here.



So, there is a Translational Constraint along the z direction, similar to the board writing process that we discussed in the last slide. So, you need to generate a constant force along the z downward direction to maintain constant contact. Once that is established, there is an external loop that allows further movement downward to be stopped, okay? So, once you establish a contact and go a certain distance downward, you need not go further down. So, you stop further going down. So, the Z-direction is limited, okay? Now, the X and Y directions. So, force-guided motion along the XY plane is done. An external force control loop with the inner position control loop is taken here. Why? Because you have to command for the position. So, wherever you want to go, you continuously tend to go there by giving a position command, but externally, it is force-limited. So, while doing the machining process, there is a machining force along the XY plane that constrains the motion. We have to check the forces continuously. You cannot apply an infinite amount of force to go to the position-commanded trajectory. Instead, this is a force that is stopping it from going there, and further, with a constant force, you keep on moving in a particular direction. So this is known as force-guided motion.

So, external interaction, that is, the milling forces, regulates the speed of the tool along the commanded position or that position trajectory and keeps that trajectory intact. So, the trajectory is not changed, but the speed with which it is moving is regulated by the forces because you have an external force control loop. So, this operation is a little bit different from the board writing process when we assume there are no frictional forces along the XY plane, that is, the plane of the board.

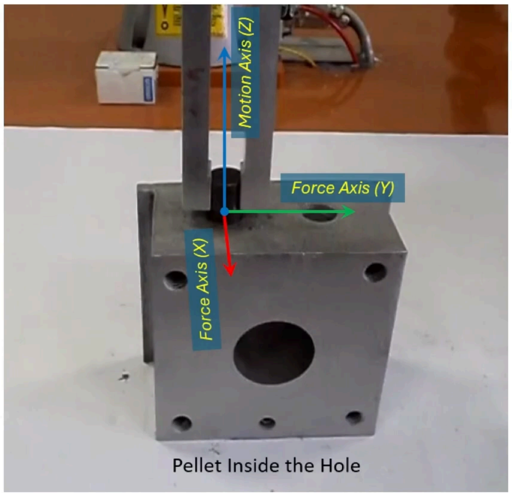
There are no rotational constraints here, but still, we do not prefer doing the roll and pitch or even yaw motion. Yaw motion is anyway redundant; we should not do that, but we also do not do this roll and pitch motion for this robot. The frictional and the cutting forces are along the X and Y directions.



The next one is a peg-in-a-hole task, which is inserting a pellet, which is the cylindrical pellet, inside a hole drilled in the surface. Okay, so how is that done? Let us again look at a small video. This is a Cobot; it starts from the home position and picks up the pellet in position control mode only, okay. It goes vertically above the hole using a vision system, maybe, and lowers vertically in force-sensing mode. Now, it is lowering, but it also monitors the force that is coming in. As soon as it establishes contact, it starts searching for the hole, and the pellet is inserted. So, a close-up of the lowering, contact, and the search process. Finally, the insertion process is shown here. So, this is a Kuka iiwa robot, which is a Cobot.

Constrained Motion Tasks

CASE 3: Peg-in-Hole task (Video)



Hole search operation:

- Peg is outside the hole and slides on the surface maintaining a constant reaction force.
- The case is similar to a pen sliding on the board.

Peg insertion task (moves inside the hole):

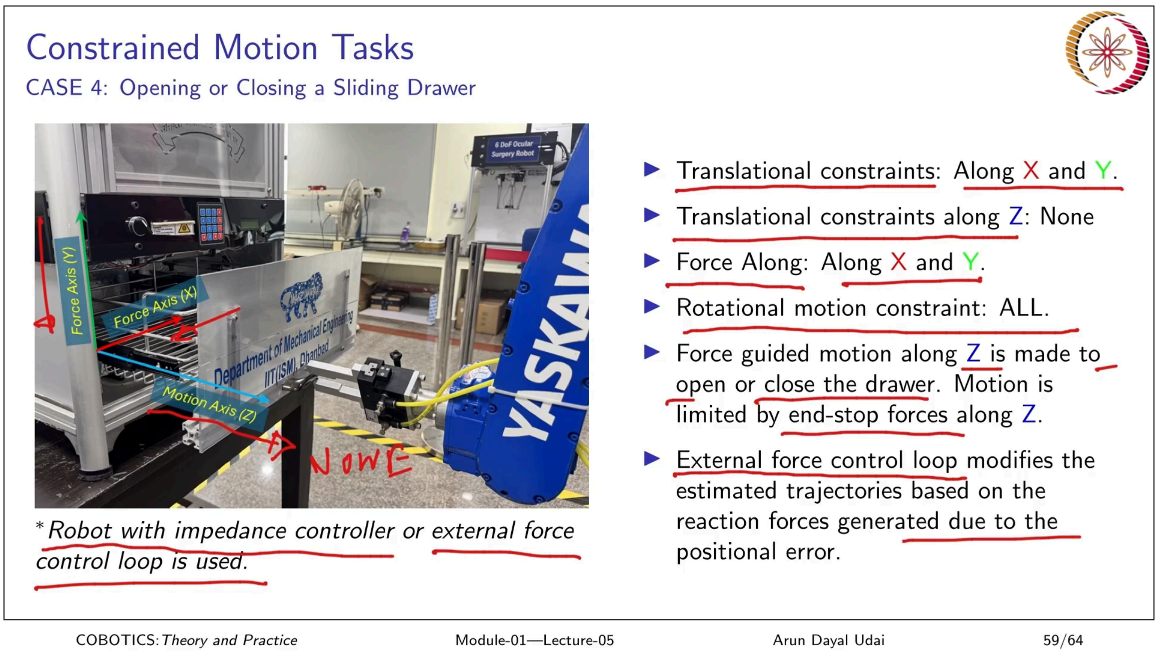
- Translational Constraints: Along X and Y.
- Force Along: X and Y directions.
- Free to move along vertical Z direction ↓.
- Force guided insertion takes place.
- Rotational Constraints: Along X and Y directions.
- The peg is inserted/released upon sensing a drop in the vertical force.

So, in this case, there are two operations. First is the hole search operation. The next one is the insertion task. The constraints are different in both cases. So, when the peg is outside the hole when it is literally very much off the hole, then you can move it in position mode. When it is on the surface and outside the hole, the robot slides on the surface, maintaining a constant reaction force. While it is searching, it does maybe spiral search or some other kind of search, a lissajous search for rectangular subspaces. So, in those cases, it searches for the edges and continuously monitors the forces, and finally, it finds the hole. Hole searching is a different algorithm altogether. So, as soon as it finds the hole, It simply drops the pellet if it is gravity-supported or it simply does the gravity guided or the force guided insertion process. That is the second phase of it. This case is very similar to the pen sliding on the board. I assume there is no frictional force again.

Now, the pellet insertion task moves inside the hole. This time, there are two constraints. The one which is shown here it is with the peg insertion task that is inside the hole. Translational constraints are there along the x-axis and the y-axis. So, those two axes, you get the reaction forces if you move a little off. So, the force axis is along the X and Y directions. Free to move along the vertical z direction. As soon as it finds the hole, it is free to move along the z direction, and it cannot produce any force.

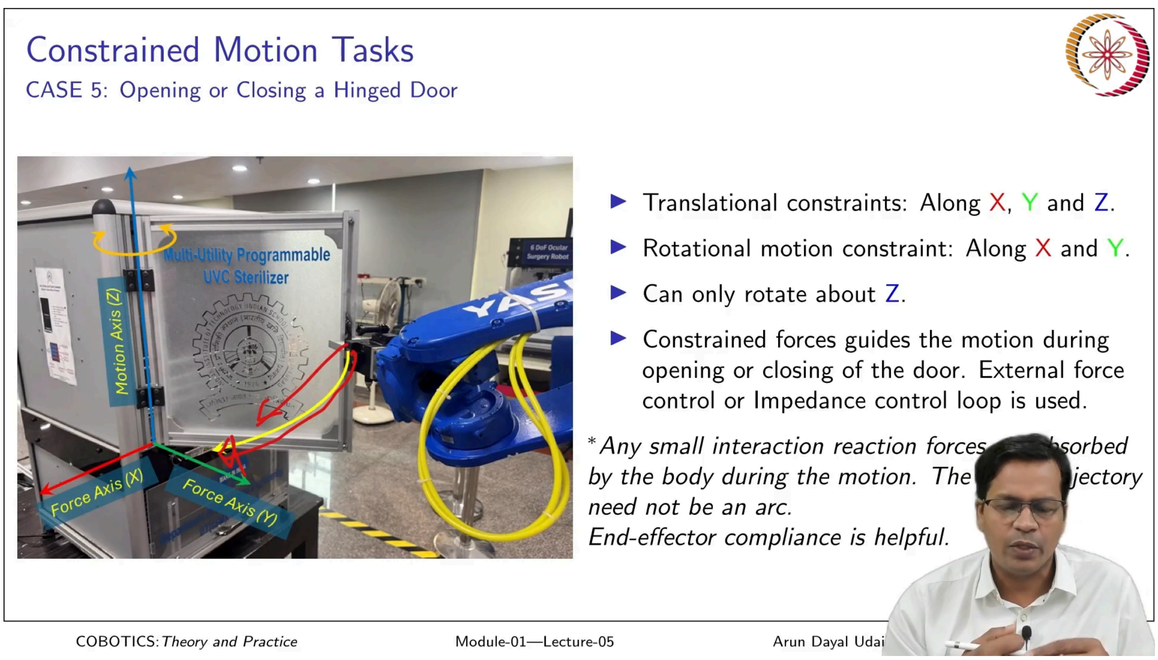
The force-guided insertion takes place. So, if it gets a little bit off, you have to come back, or the end effector compliance of the impedance controller takes care of that, and finally, you can push it inside the hole, or you can just drop it if it is gravity-supported.

Rotational constraints along the X and Y directions exist. You cannot roll, you cannot pitch also as soon as it gets into the hole. The peg is inserted and released upon sensing a drop in vertical forces. How does it know, actually, that it has reached the hole? Actually, it continuously senses the z-direction force. There is a sharp change in the force value as soon as it gets to the hole, and it drops or pushes it in.



Now, the next one: The Opening or Closing of a Sliding Drawer. A drawer can be of many types, but this is a sliding drawer in which this board can get in and out. So, this is the constraint here. So, you have a motion axis that is along the z-axis again, and the X and Y directions are fully constrained. That means your robot cannot displace along those directions. So, in this case, translational constraints exist along the X and Y axes. Translation is constrained along the z-axis; there is none. So, it is free to move along the z-direction. So, it can produce forces along the X and Y directions if it is perturbed.

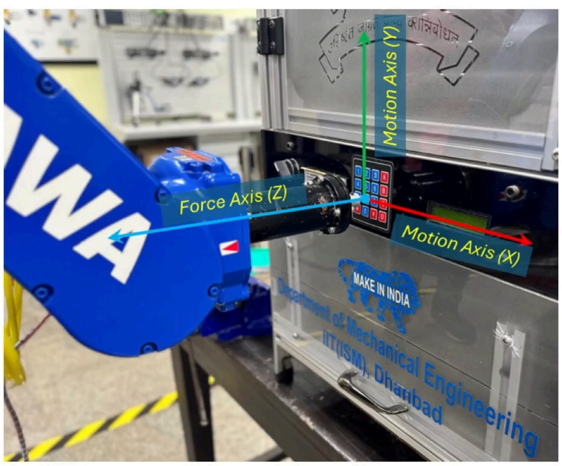
So, this kind of assembly again requires an external force control loop or, in the case of a Cobot, it can be an impedance controller. It has quite a good amount of compliance along all the directions or programmed compliance along those directions. Rotational motions have all the constraints; they cannot rotate in any direction. So, what happens in a force-guided motion along the z-axis is made to open or close the draw. Motion, which is limited by the end-stop forces along the Z-axis. So, as soon as it feels a jerk when it reaches its limit, it stops. So, what is the modifier here is the external force that is because you do not know the straight-line path with which you have to pull it out. So, you do not know that path. You can simply pull it out in any of the estimated directions. So, this force, basically these X and Y forces, which are generated out of the reaction forces, will correct the trajectory. Because of the compliance, that trajectory gets corrected based on the reaction forces that are generated due to the positional error or the trajectory error. And finally, it is opened or closed.



So, this is case 4, and case 5 is Opening and Closing a Hinged Door. So, a hinged door has an axis about which it can rotate. So, again, in this case, there is a translational constraint along X, Y, and Z. Like the earlier one had a rotational constraint in all directions, this one has a translational constraint in all directions. It cannot translate in any direction. But yes, This point, where the robot is actually interacting with the door, is supposed to move in an XY plane. So now, the rotational motion constraint is there along the X and Y directions. So, you cannot rotate about x, and you cannot rotate about y, while it can only rotate about the Z-axis. So, the constrained forces guide the motion during the opening and closing of the door. External force control or an impedance control loop is used. Any small interaction forces that generate the reaction force are absorbed by the body during the motion. The body may be the robot, or it may be the handle, where there is some compliance or clearance. The input trajectory need not be the arc that is shown here. So, you can simply move it in a straight line. Thus, the forces become the modifier of the input trajectory. So, the input trajectory could be a straight line along this path, or it could be an arc that is approximately in the x-y plane. So, yes, in this case also, end effector compliance or any clearance is very helpful, and this is the way these types of tasks are done.

Constrained Motion Tasks

CASE 6: Pressing a button

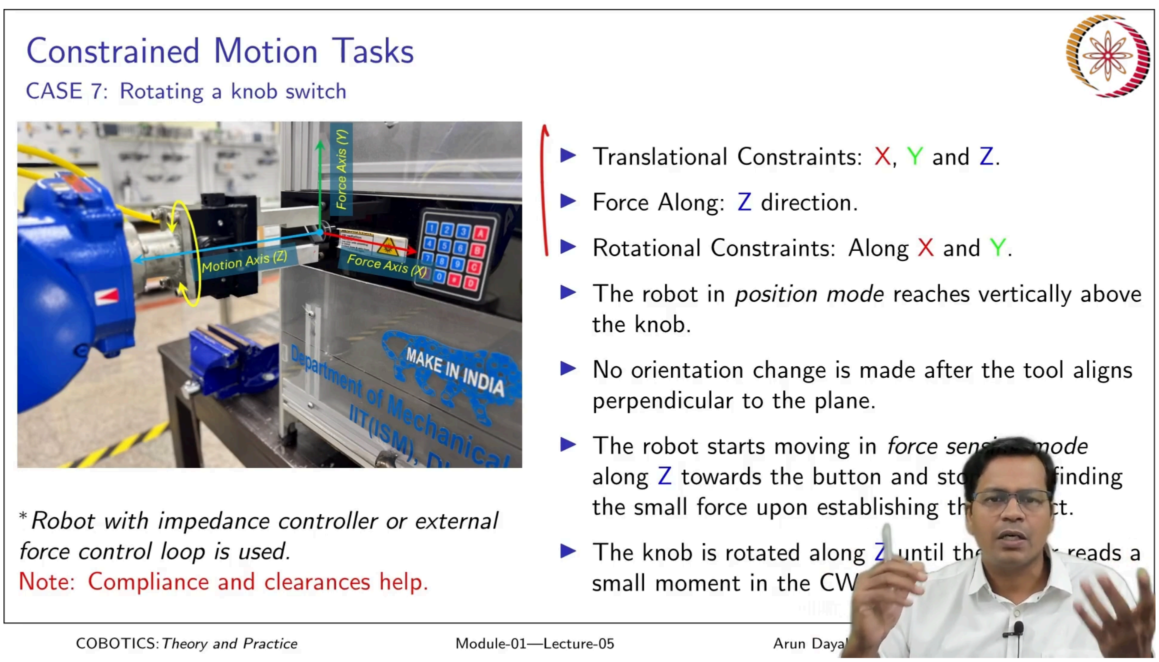


- Translational Constraints: Z.
- Force Along: Z direction.
- Free to move along X and Y.
- Rotational Constraints: None
- The robot in *position mode* reaches vertically above the button.
- No orientation change is made after the tool aligns perpendicular to the plane. (May be vision guided)
- The robot starts moving in *force sensing mode* along Z towards the button and stops upon finding the small force upon establishing the contact.

The next one is Pressing a button. So, again, this is very much like writing on a board. You see, you have motion axes along the X and Y directions, and you have to maintain a small force perpendicular to the button in order to press it, but to reach vertically above this button could be vision-guided. So, let us discuss the constraints here. It is a translational constraint along the Z direction. Along this, you cannot move, but yes, you can definitely lift it off the button. Force along the Z direction you can generate, and it is required. Free to move along the X and Y directions. Rotational constraint, there is none, but yes, that is not advisable. Also, the robot in position mode reaches vertically above the button using some, maybe a vision, which is their vision system that detects exactly the button that is to be pressed, and then you reach vertically above that.

No orientation change is made after the tool aligns perpendicular to the plane. Again, this may be vision-guided. You detect four corners and detect perpendicular to this plane using some kind of marker that may be there. And perpendicular to the plane, you align your robot along that. You reach vertically above the button. Go gradually downwards in force sensing mode along the Z direction. As soon as the contact is established, you apply a small amount of force based on the force sensor reading which is there.

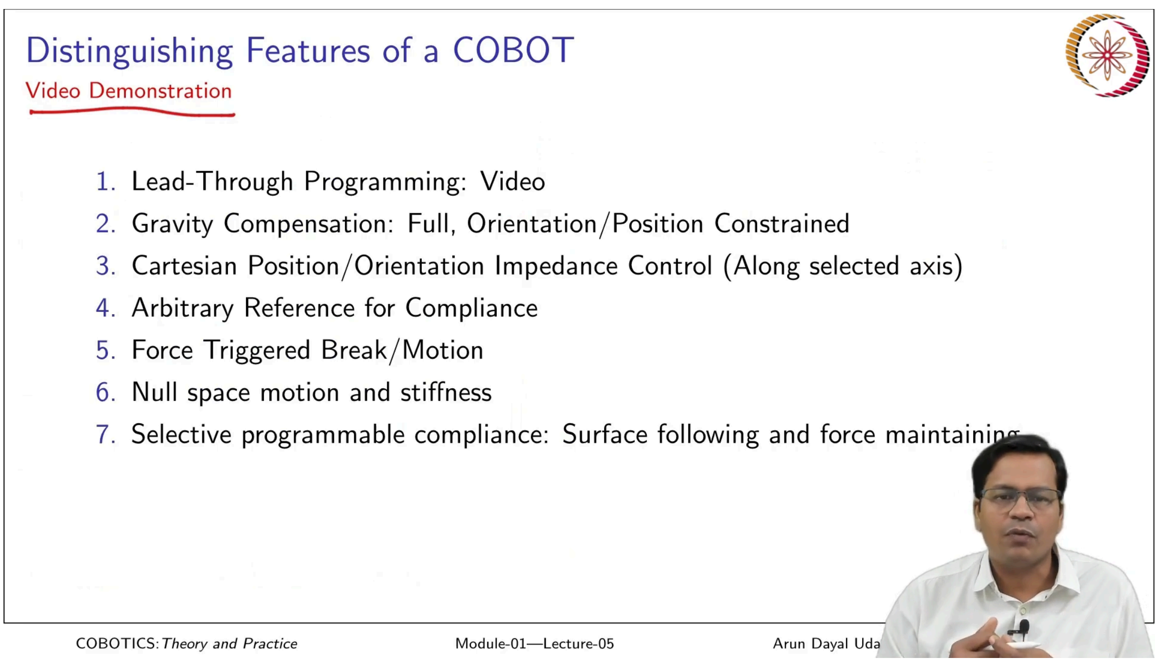
So, the robot starts moving. In force-sensing mode along the z-axis towards the button, it stops upon detecting a small force upon establishing contact. So, this is how these tasks are performed.



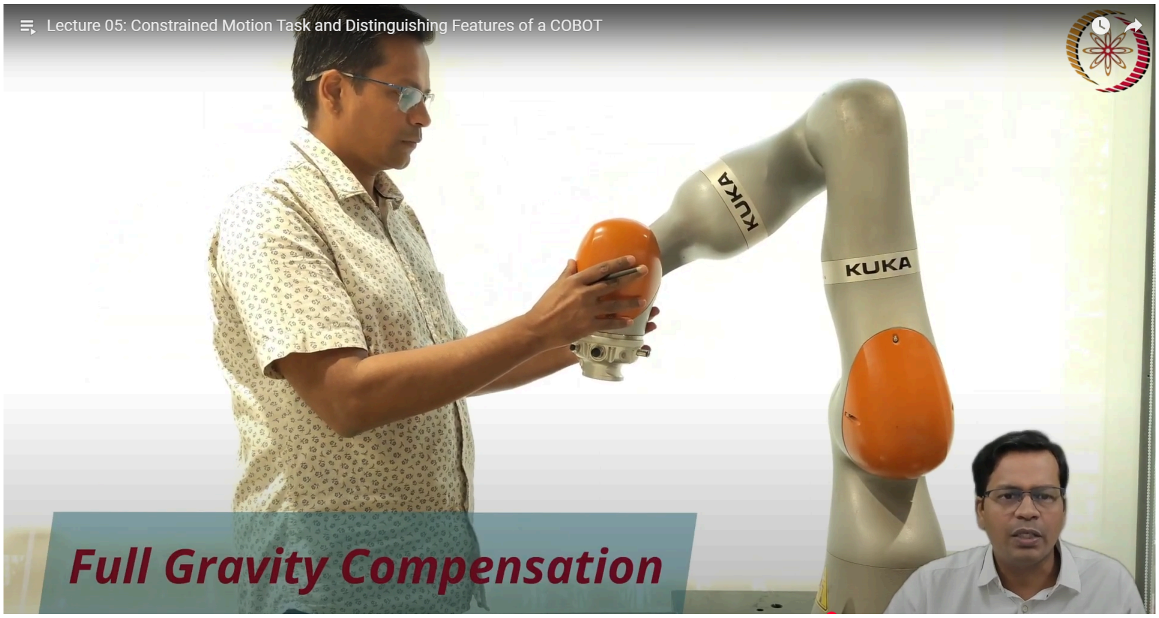
The next one is Rotating a knob switch. Knob switch. How is this done? Again, you need to have an impedance controller or an external force control loop in the case of a standard industrial robot. This could be a Cobot also. So, compliance and clearance are definitely going to help you here also. Translational constraint: you cannot translate. Once you have held the knob, you cannot translate anymore. Force along the Z-axis is required to establish the contact. Vision guidance is needed to get to the position where your knob is, how your knob is oriented, and to establish yourself exactly above the knob. Rotational constraints are along the X and Y axes; you cannot rotate. The robot in position mode reaches vertically above the knob.

No orientation change is made after the tool aligns perpendicular to the plane. So, this is the place I am talking about. So, you may again have markers normal to the surface detected, and the robot is aligned exactly perpendicular to this surface before lowering to the surface. The robot starts moving in force-sensing mode along the Z-axis towards the button and stops upon detecting a small force upon establishing contact.

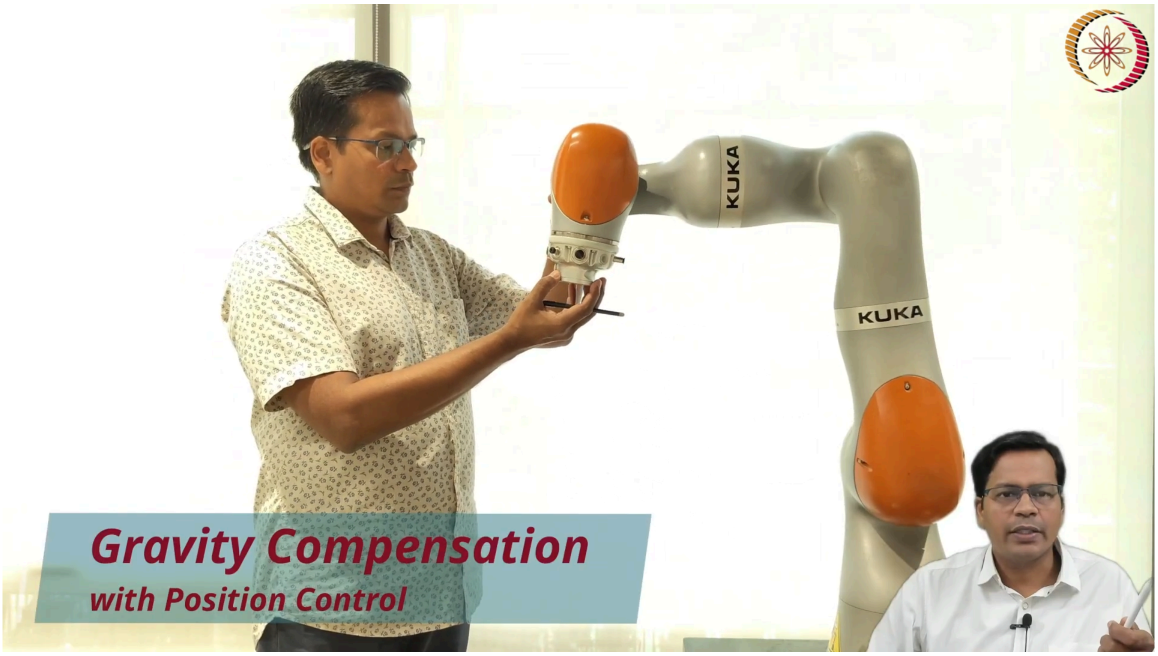
The knob is now rotated about the Z-axis until the sensor reads a small movement in a clockwise or counterclockwise direction, whether switching it ON and OFF. So, this is how these operations are done, and these are the constraints. So, this is all about the constraints. So, to do day-to-day tasks which a Cobot or a human normally does in their day-to-day life.



So, these are the videos I used to demonstrate the features of a Cobot, that is, the capabilities of a Cobot.



So, this is a gravity compensation task. What is done here? I am able to drag the robot to any location, and this gravity compensation task here is essentially maintaining the orientation. But I am able to take it to any position: x, y, z. So, that is being done here. So, it is fully free; it is gravity-compensated. Active gravity compensation is present. Live sensors provide the robot with feedback. The controller continuously applies the gravity compensation torque and is able to do this. This is a wonderful thing when you can easily teach. With full gravity compensation, you can even change the orientation, you see. End-effector orientation can also be changed. I am able to rotate perform roll, and pitch operations. I can drag it to any X, Y, or Z point. This is full gravity compensation. It becomes very difficult when everything changes, and this is a redundant robot. It has seven degrees of freedom. I am actually taking it to a point that needs to be taught. I took it there and brought it back. So, it may help me teach that point.



Now, it is under position control. So, I can change the orientation, but the position is controlled. You can do this also. This is again a gravity compensation example, where the orientation can change, but the position of the end effector or any reference point can be kept stationary. So, I am able to move around that point. The whole robot can move around that point. Got it?

Now, Cartesian stiffness is along the XY plane, but it is free to move along X. So, along the X direction, which is the back-and-forth direction, I am able to pull or push this robot, but yes, in other directions, it has stiffness. It may be set to some 100 Newtons per meter or something like that. So, it is programmable stiffness that I can put in the task space.

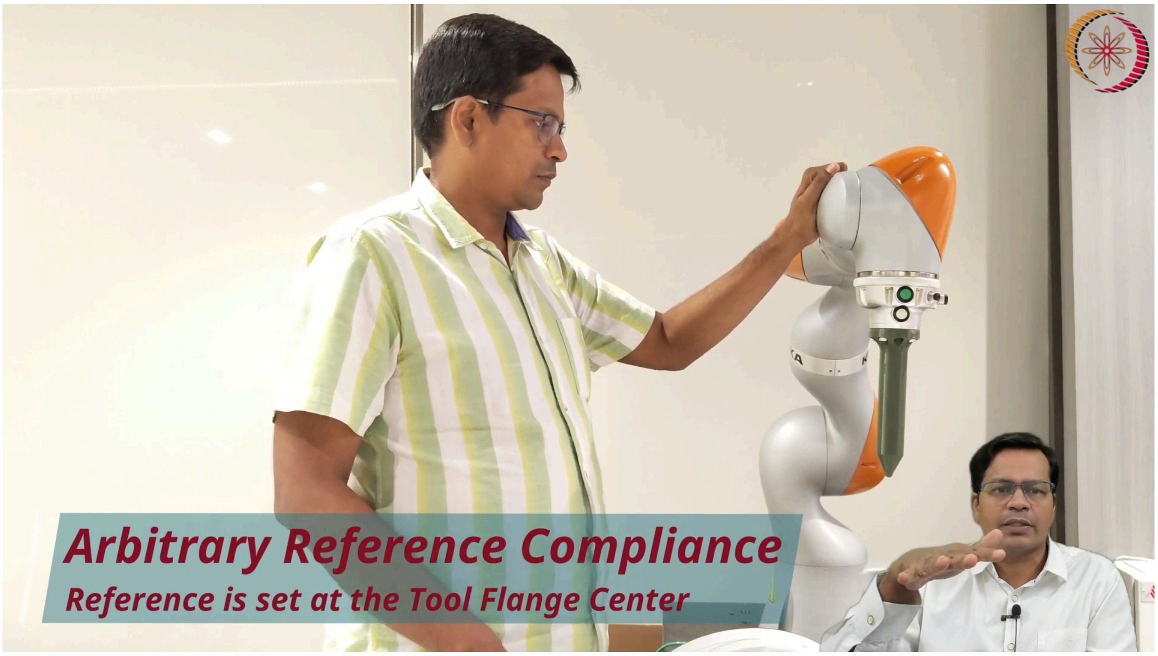
Again, it is along the XY plane, free to move along the Z direction. So, again, in the X direction, there is some stiffness; along Z, it is free; along Y, I also cannot move it; there is some stiffness. So, this is all Cartesian stiffness. These are some very, very special features that can let it perform some special tasks.

Now, it is free to move along X, Y, Z. Stiffness is set to 0. So, this becomes very much like a gravity-compensated, position-controlled robot. It can be dragged to any place in 3D space.

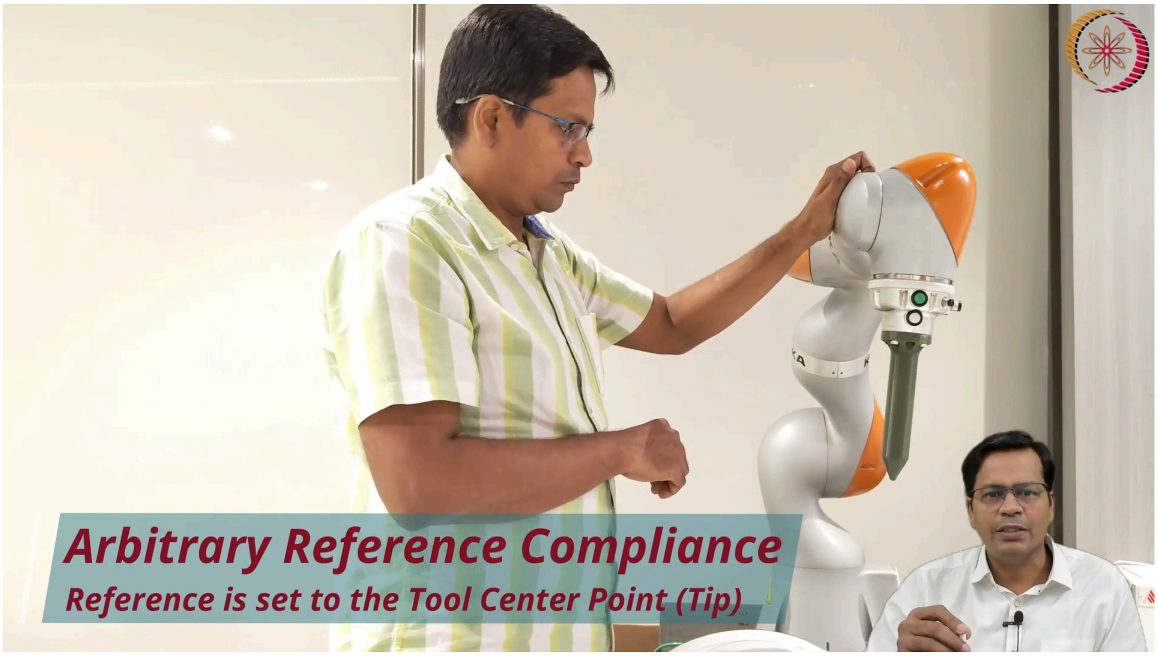
And now it has Cartesian stiffness along Z but is free to move along XY. So, I can move it on the XY plane, but not in the vertical downward direction. So, there are multiple ways you can have compliance axes and free axes.

So, Then, it has Cartesian stiffness control with different values along each direction. So, in this direction, you see it has very low stiffness; in other directions, it is even less, but in the vertical direction, it may have a slightly higher one. So, all the directions can have different stiffnesses again. Maybe you are handling some load in the vertical direction.

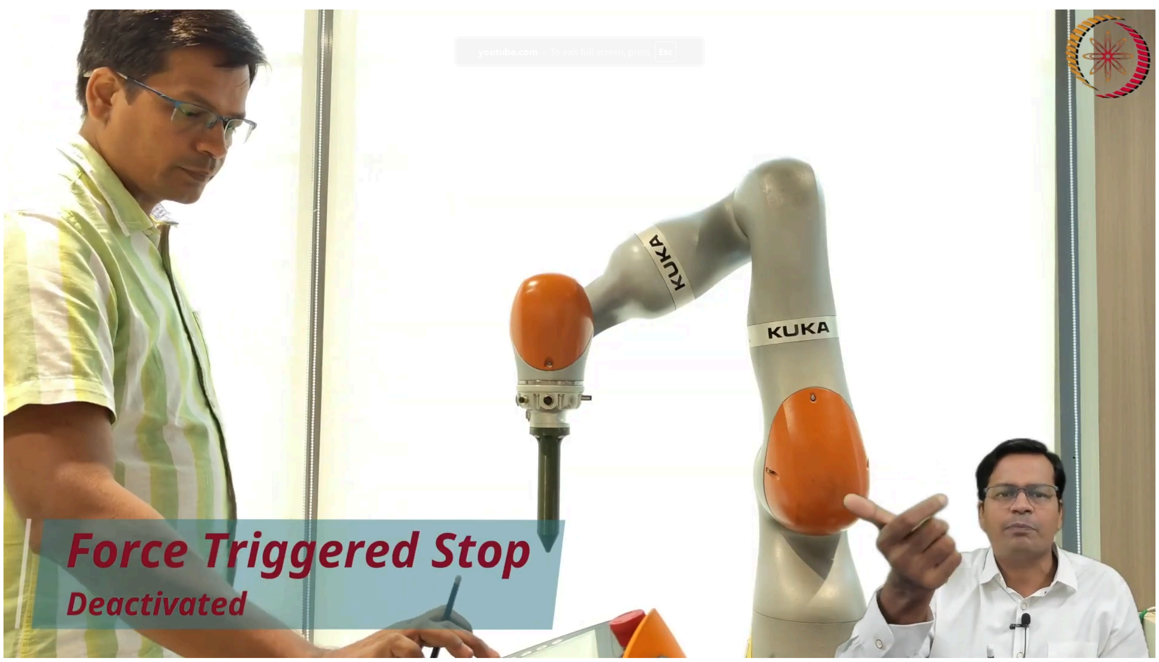
So, this is Orientation Stiffness. So, about that point, you can have different stiffnesses, angular stiffnesses along each of the directions x, y, and z. But it can maintain the position. See, it is maintaining the position. But I can change the orientation about that position. This point can be changed as well. So, now it is at the flange centre.



It can be an Arbitrary Reference Compliance also. The reference point is set at the flange centre. I have just attached a tool so that you can observe it carefully. This time it is about the center of the flange that the orientation is changing, and that point can be somewhere down below or somewhere else.



So, it is at the tip of the tool about which I am able to move it also. Again, stiffnesses can be changed around each of the directions. This type of thing is very useful when you do, maybe, a skin-penetrated laparoscopy tool that you have inserted. You want some point to remain stationary. You can put that point as a reference point.



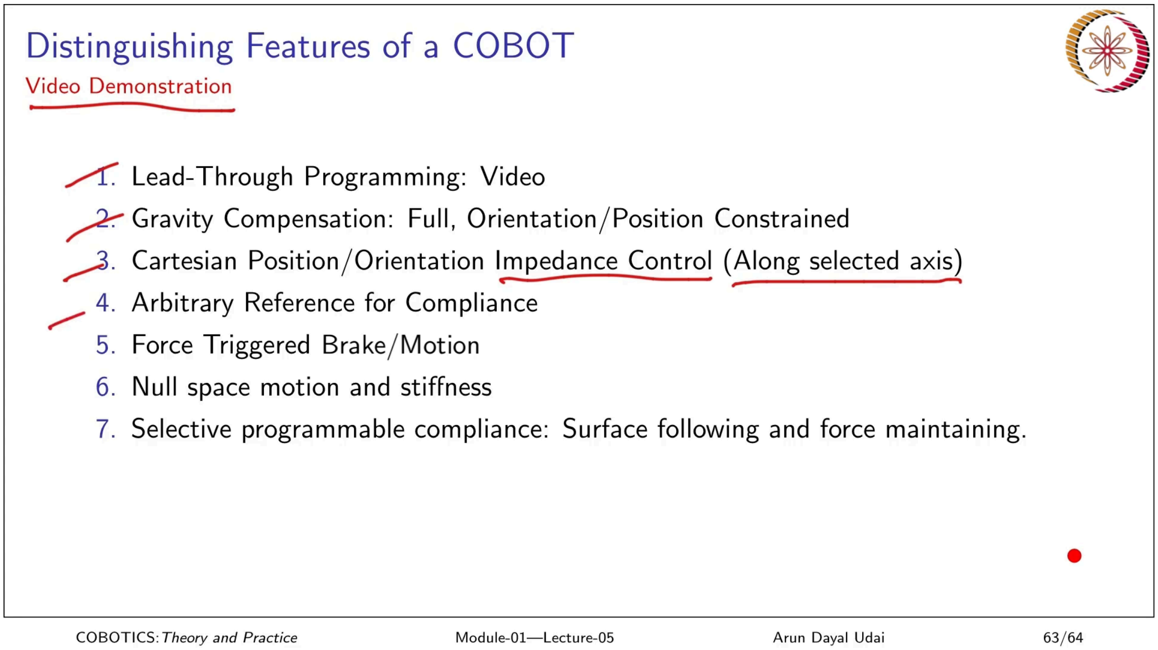
Force-triggered stop. See, initially, it is moving downwards and it does not sense any force. I am hitting it. So, it has no sense of force. Now, this time, force is triggered, and stop is activated. Yes, as soon as I hit it, you see it has stopped. It can be started with a force, stopped with a force, or started with a force. This is null space; this is a 7 Degrees of Freedom robot when it has infinite solutions to go to a place like an end effector pose is fixed while joint angles can change, and even that stiffness can be adjusted.

Stiffness is increased. I need a little more amount of force to adjust that. It comes back to that. End effector stiffness is also there.

This is selective programmable compliance, arbitrary surface following with force sensing you can do. So, yes, in this case, a vertical downward force is maintained while I am giving motion along the y direction. In one of the directions, I am giving motion. So, it is maintaining the force. When it is elevating, it simply comes up. It simply comes up.

I am moving the table, and the profile is unknown for the robot. It also follows that. So, an unknown trajectory can be followed. You just maintain the force and move from one end to the other end. You can simply do this operation. So, I am moving the table in a different orientation. It is still able to track the trajectory. The surface profile is able to do it. So, maybe in a kind of grinding, polishing, or buffing task, this can be very, very helpful.

There are stiffnesses along the X and Y directions. In the y direction, I am moving. In the X direction, there is stiffness. In the Z direction, there is force maintaining. I can lift it because I have only set 10 Newtons.



So, this is, these are a few videos that you have seen. Lead-through programming, gravity compensation, Cartesian positioning, impedance control you have seen along each selected axis, arbitrary reference compliance, force-triggered break or motion can be done, null motion, and selective programmable compliance. So, these are some of the capabilities of a standard Cobot, which you should look for if you are looking for a good Cobot.

So, yes, these are Control algorithms that go behind, which we will be discussing later in our course also. So, yes, for this lecture, I will end here. In the next lecture, we will start with Cobot Actuators, Sensors, and Safe Workspaces.

That is all. Thank you very much.