**NPTEL Online Certification Courses**
**Industrial Robotics: Theories for Implementation**
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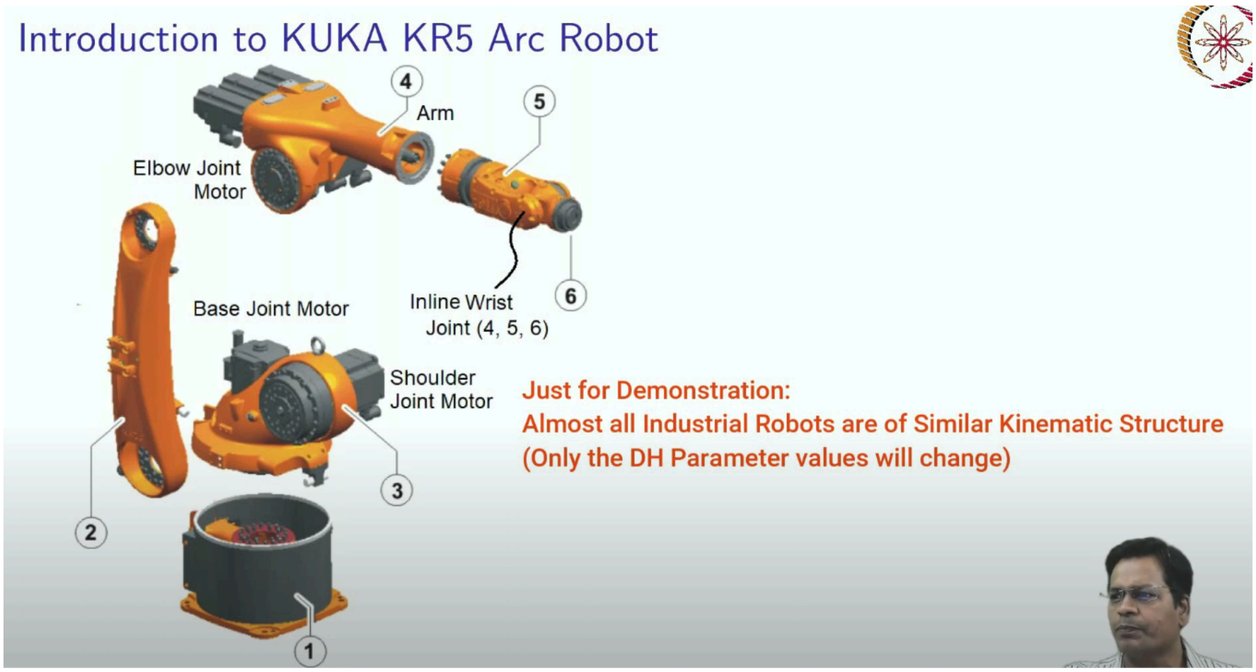
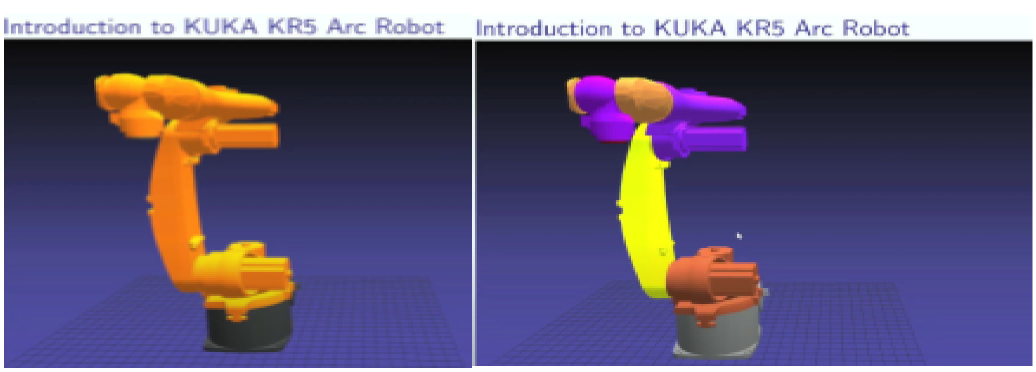
**Week: 04**
**Lecture: 20**

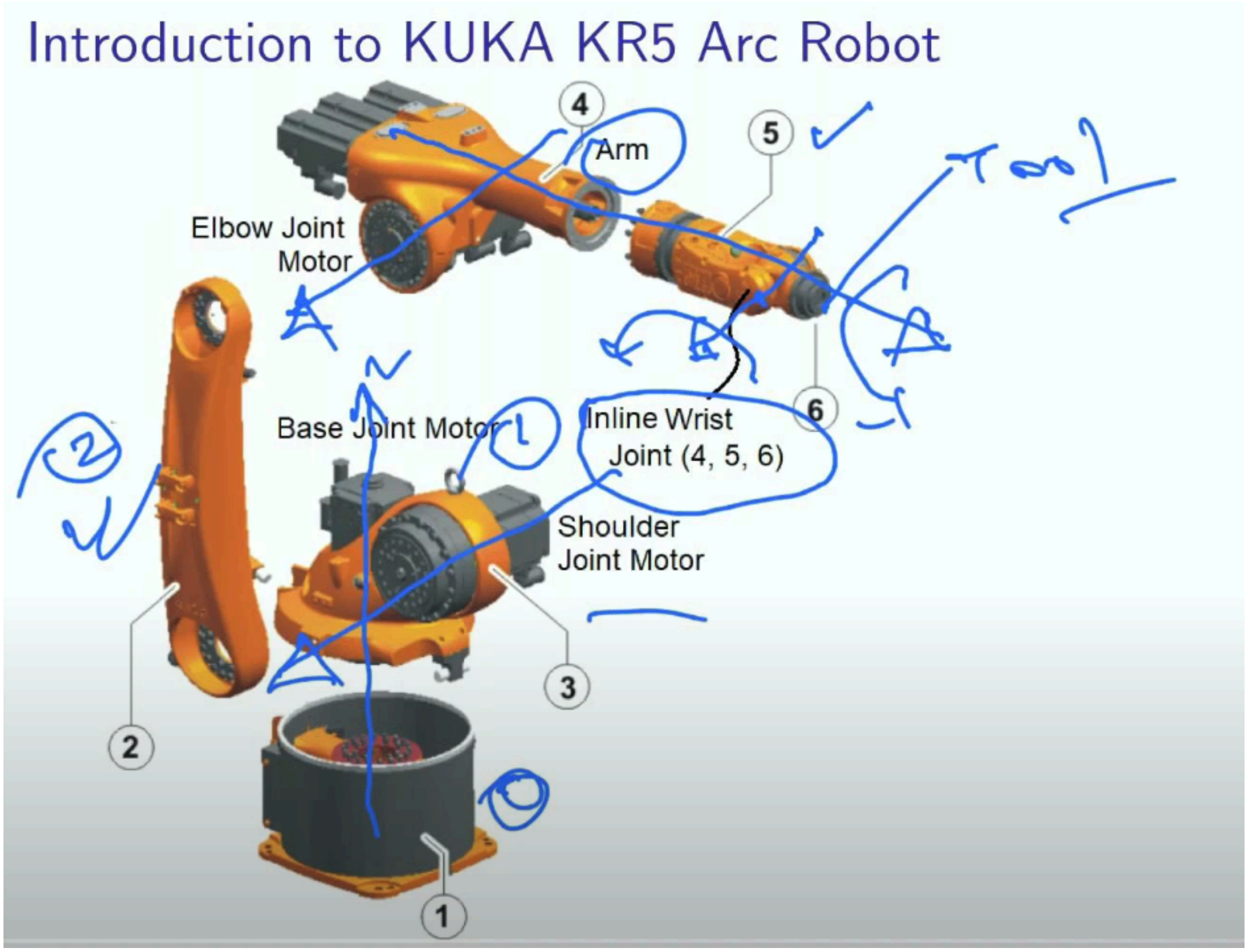
# Forward Kinematics of 6-DoF Industrial Robot.



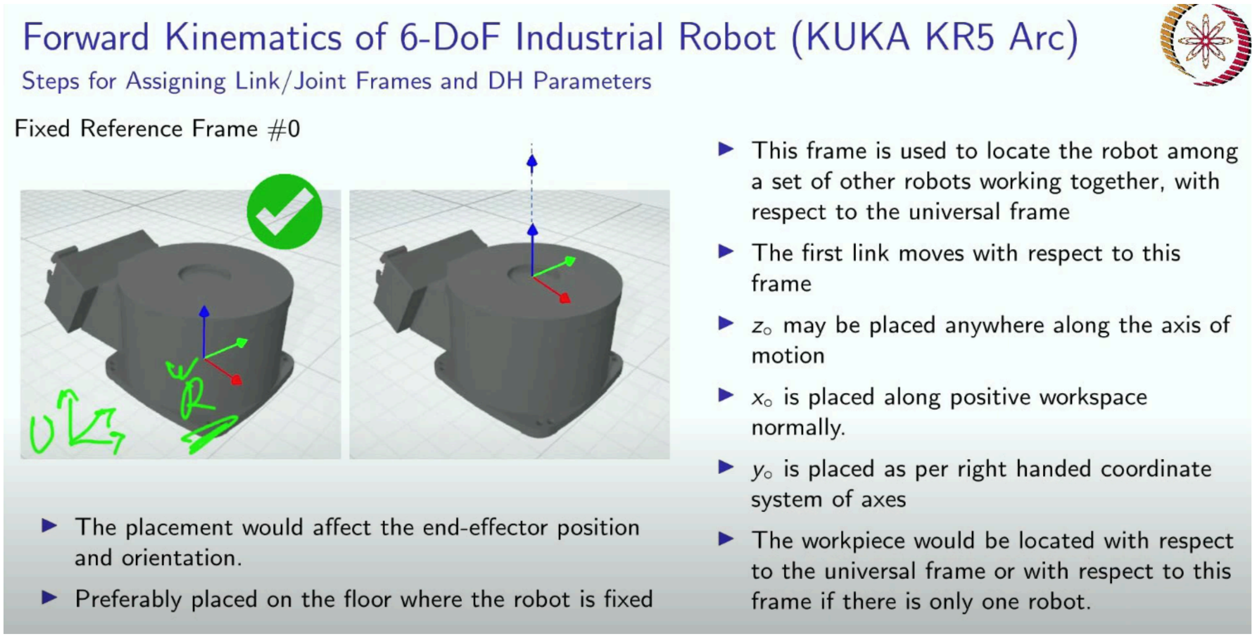

Welcome back to the module forward kinematics and kinematic transformations. Moving ahead, today we will be doing a real industrial robot, which is a six-degree-of-freedom robot. So, let us start with today's lectures. Let me introduce you to the KUKAN KR5 Arc robot. I'll be using this robot actually to demonstrate forward kinematics.



So, before we begin, let me just show the motions motion capabilities of this robot. So, yes, it looks like this. By default, it has some orange type of colour. Normally, all the industrial robots are bright so that in the industrial environment, it is easily locatable, and you can see the motions they are making so that you can be safe. Now, let me just colour it with different colours so that it becomes easy to identify the links that I want to cover today. So, yes, if it is something like this. So, here goes your first motion that it can do. So, you see the bottom one on which it is mounted. The grey colour over here is static, and that is mounted with some grouting bolts to the ground, so it is not going to move. The first link is the motor that you see here. This is the motor that is actually giving it a vertical axis motion. Okay, vertical axis motion. So, here it is. So, it is making something like this. The second motion that it can do this is known as a shoulder joint. Okay, the first one was the base joint and this is the shoulder joint. You see, this is moving. The yellow link which is there next, and then you have an elbow joint. This is an elbow joint. There is a motor over here to move it. This moves the purple-coloured link, which is here, Okay, and then you have axis 4, which is here, that gives you a motion that comes till the wrist, and you see axis four and axis five motion and axis six motion. That is a small tool which is over here, Tone pose that is moving, Okay, so I should make it like this so that it is easily visible to you. Okay, you see axis 6. It moves like this. So, all three axes are, you know, intersecting at the point which is known as a wrist centre point. Okay, so this is how it is. So, let me come back to my original picture.

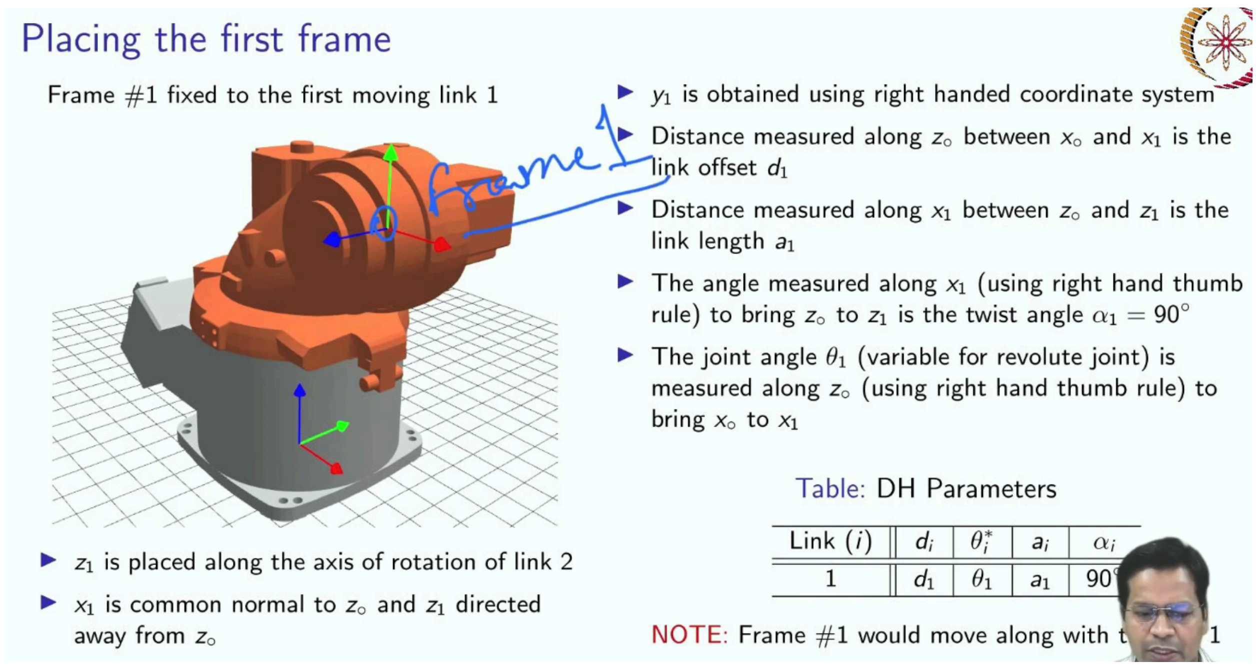



So, this was your length one. So, you see, you have link one, which is here, so this whole assembly, this whole assembly, along with the rest of the robot in assembled condition, could rotate about this. This was the base frame. Okay, then comes the next axis, which is here. So, this was your first axis, if you can make a straight line over here. So, this was your first axis. The next axis is something like this: you see, Okay, this moved this link. So, this is your zero frame. Okay, zero frames, which could be attached here. The first link is something like this: this is your second link, which was moved by the shoulder joint which is here. The base one was vertically like this: Okay, now you have an elbow joint again that is like the previous one. This is the elbow joint that actually moves the arm, which is here, the arm which is extended right till the front. Okay, so this is axis.4. Okay, and then you have axis 5. That comes very much over here. Okay, so axis four can move along this axis. Okay, about this axis, you can make it rotate. This is axis 5. And then you have the last one, which is here. Okay, that is the tool post. It is the tool post on which you mount all the tools. That is also known as an end effector. So, you see, you have a wrist centre inline wrist joint which is interred, an intersection of axis 4, 5 and 6 together over here, and you have a tool post, which is here, on which you can mount all the tool.




So, let us start doing forward kinematics for this. So, here we go. This is your first base joint. So, you have to have some reference frame fitted on it. That is, we'll call it frame 0. The placement would affect the end effector's position and orientation. So, the first frame, which is here, about which you will be expressing your end effector, you will be analysing, you will be finding out the end effector position with respect to this one, Got it. So, that is why placing this frame is very, very important. So, you see, if I place this as a positive x-axis, if your robot is right ahead, it will show some positive x displacement if it is in that direction. So, your coordinate, your end effector position, will be based on the frame which is placed here. So, this is very, very important frame. It can preferably be placed on the floor. Normally, we place it on the floor where the robot is so that you can actually get the end effector position with respect to the place where it is grouted, not with respect to a point which is somewhere on a little higher up from the ground. So, it becomes very, very convenient to locate your end effector position exactly. And you know all the robots which are there in the workspace. They all will have this robot base frame. This is known as the robot root frame. So, this frame- R1, R2, R3 and so on, so forth, for all the robots will be there on the same floor. So, that is, that is the reason why it is so convenient to place it here. But anyway, you can place it anywhere along the axis. This frame is used to locate the robot among a set of other robots which are working together, as I told you, with respect to the universal frame, which may be somewhere in the workspace as well. Okay, that the first link moves with respect to this frame. Now, because I know the next link which is going to come is going to rotate, something like this. So, I have placed my z0 like this, so this becomes your z0, about which your link one will rotate. Okay, so this becomes the axis of rotation for the first link. Now, z0 may be placed anywhere along this axis, as you know, but I have conveniently placed it here, and then x0 is placed along the positive workspace.

Normally, I prefer putting it in this direction so that I want to see all the time, all the coordinates of my robot as positive because I know my robot is going to be in this region most of the time, so every time, it will be positive, at least along the x-axis. Okay, y0 is placed as per the right-handed coordinate system of axes. If you know where your x is, you know your z, so z cross x should give you y. So, y is placed like this. So, this is the reason why it is placed like this, so I prefer working with this one. Okay, the workpiece would be located with respect to the universal frame, so you know now that I have placed it here. So, the universal frame is somewhere over here that may be in this workspace. This was the robot frame so that that workpiece would be located with respect to the universal frame or with respect to this frame. So, when there is just one robot, it is this frame that becomes everything for the robot system, so let me just disappear so that you can read carefully.

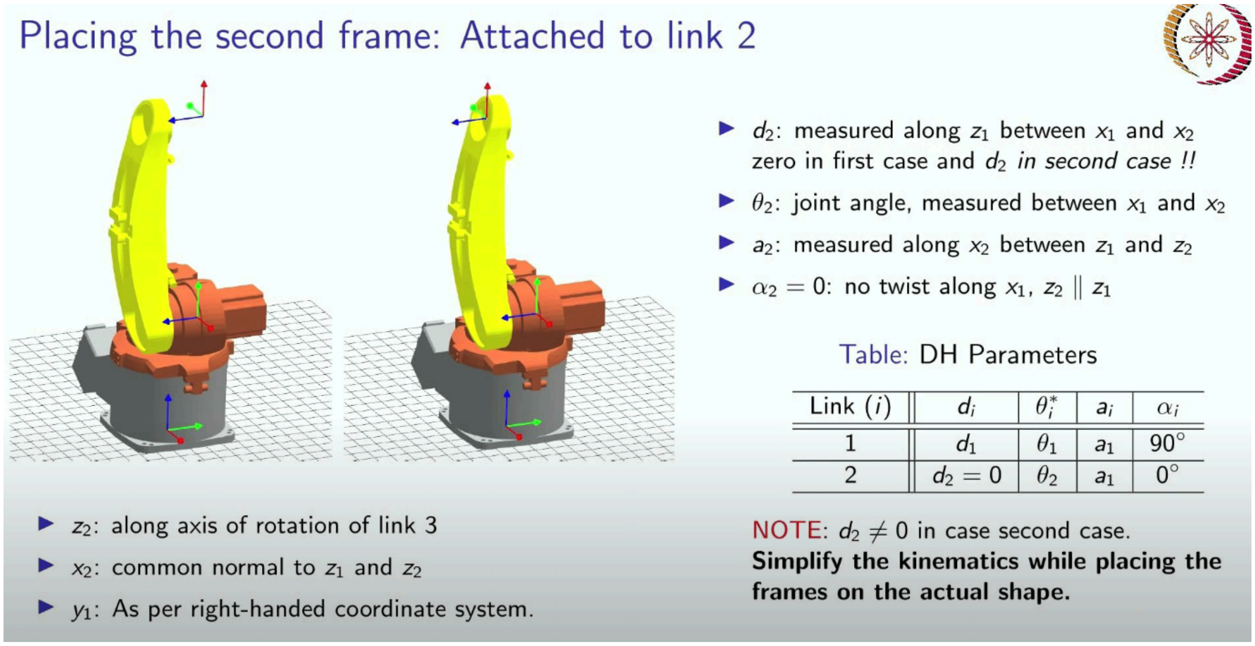



So, this is your next link. So, now that I have already placed my first frame with z0 like this. So, now, I will move on to this one. Frame one is placed at the end of link one where you are going to attach to link two. So, link two will be moving with respect to frame one, so this becomes your z1. Got it, if I can show you, once again, using this robot at least. So, this was your first axis, so first frame. You see, there is a motor here. There is a motor here that is going to rotate. This link got it. So, the next axis will rotate along with the link one. So, this is yours. This first assembly is your link one, the brown one in the virtual figure you can see. So, this is it. So, this is your axis. So, you got it. So, this becomes your z1.

So, now let us begin. So, z1 is placed along the axis of rotation of link two. Got it? So this is your link two. So, this is your link two. So, that is moving with respect to link one. That is this one, this brown one. This is your link one. x1 is common normal to z0 and z1. So, you see where you have to put x1. X1 is in red over here. So, this is a common normal to z0 and z1 directed away from z0. So, if it is z0 like this, and this is your z1. So, the common normal is like this. So, this becomes your h0, so it is directed away from z0. So, here it goes. So, it looks like this. Got it, got it.

Now, Y1 is obtained by using a right-handed coordinate system. That is quite useful. So, if you know x, you know z. you also know you use Ruth's coordinate system, the right-handed coordinate system. So, distance is measured along z0, along z0, and between x0 and x1. So, where is your x0? This is your x0. This is your x1. So, distance is measured along z0. So, this is your z0. So, z0 distance between them. So, this is your distance. Is the link offset d1? So, this is your d1, got it? So this is your t1. Now, distance measured along x1, between z0 and z1. Now, find out where is z0 and z1. So, again, this is your z0, this is your z1. And distance now is to be measured along x1. So, this is here. So, if you extend it behind, it intersects here and here. So, this is the distance. And what is this? This is the length of the link. That is a1, so you got it. So, this is your a1.

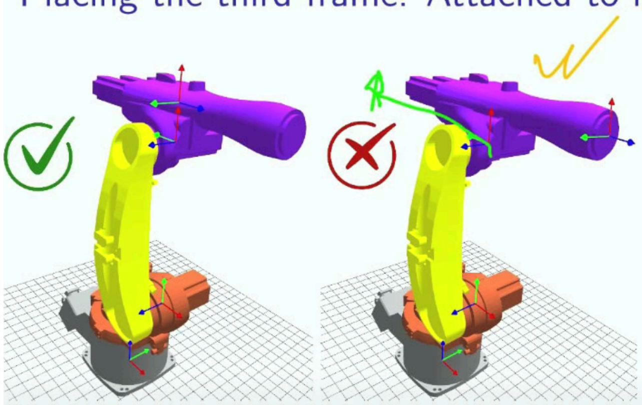
The angle measured along x1. Angle measured along x1, using right-handed thumb rule to bring z0 to z1. So, again, this was your z0, this was your z1. I have to bring z0 to z1, z0 to z1. That will become my twist angle, so you see. It is rotating in a counterclockwise direction, that is, if you measure it from here. So, it has rotated like this. So, that is your alpha 1. So, by an angle that is 90 degrees. So, that is your twist. Got it now. Joint angle theta 1 is the joint variable because it is a revolute joint, so it is to bring x0 to x1. So, already this is x0, this is x1. If at all there is any relative rotation between them, it will be measured about this z0, and the angle will be theta 1. That will take x0 to x1. So, looking from the top, if it is x0, this is x1, measured about a z0 axis. So, this becomes your theta 1. Got it now. This is your first parameter table for the link 1. That is this one. This is your link 1. So, d is a distance that came somewhere over here and is the link length that came here, a1. Theta 1 was the joint angle. That is, the alpha is the twist angle. Okay, that was 90 degrees. So, this is your base parameter for the first link. Now you also should note that frame one would move. This is your frame 1, frame 1. So, this frame, if this link rotates, and frame one will rotate along with that. That is what I meant here.




So, yes, now let us put the link 2. So, this is your link 2, so it is. So, frame two will be attached to link 2. So, this is your frame two that is shown here. It can be placed at two different locations, okay, so that is what I will be focusing on here, to make you understand which one is better and which one is not. So, z2: first, you have to put z2 along the axis of rotation, the axis of rotation of link 3. So, this is your link, this is your link 3. So, that is your axis of rotation, which is somewhere over here. Got it? So, this is your axis of rotation. That is the motor. So, that is moving. So, this frame is to be put somewhere over here. So, I have conveniently put z like this. So, this is your z2, got it. Now you have to put x2. That is common and normal for z1 and z2. So, this was your z1, this is your z2. So, now you have to put x2. So, x2 is nothing, but it is common and normal to this, and you can place it. So, this is your z2, and this is your z2. So, this is your z2, and this is your z2. So, now you have to put z1 over here. But I know this robot is a sagittal plane robot. That means all the. There is a situation, there can be a situation when one of these robots can lie in here to here, taking it here and then bringing it back. It is better not to move it like this. Better not to move it in this direction and bring it back. Rather, I'll just put my frames here and immediately here. That is, in a plane. So, irrespective of the shape of this link, this link can be of any shape. Okay, this yellow-coloured link. So, this frame is here, this frame is here. The link can be of any shape, but you have to put the frame here and another frame directly above that one. Okay, so that will be better. Okay, unnecessarily. Why increase the number of parameters if it can be directly eliminated? Right, while you take the frames, while you place the frames? Okay, so h2 is common, normal to z1 and z2. Y1 as per the right-handed coordinate system, as you have been putting so far. So, this becomes your y1.

Now, d2 is measured along z1, between x1 and x2. So, where is your x1? So this is your x1, and you have x2 over here. So, yes, there is no displacement between them along z1. So, this was your z1. Okay, so this was your z1, and there is no offset along that direction, along z1. So, detail d2 remains to be equal to 0. But if at all you have taken this as a frame, then d2 would be a displacement from here to here. So, that is not the case. I preferably have put it like this. So, d2 is equal to 0. Theta 2 is the joint angle measured between x1 and x2. So, you have another angle. That is theta 2. That is the joint variable. That is going to be the angle between x1 and x2 in the given situation. This is your x1, and this is your x2. So, already, this angle is 90 degrees. It is supposed to be like this, but it is like this, so it is already 90 degrees. So, that is the initial angle that need not be put. You can just put it as theta 2. In the DH parameter table, a2 is the distance which is measured along x2, between z1 and z2. So, this was your z1, this was your.Z2. So, this is your a2. That is the link length. And then alpha 2 is equal to 0. As you see, there is no twisting between z1 and z2. Z1 is parallel to z2, so there is no twist along x1. So, alpha 2 is equal to 0. So, this becomes your new DH parameter in the DH table. Okay, d2 is not equal to 0 in case the second one is the case. If this is the case, d2 is not equal to 0. Okay, otherwise, you will have to put the d2. Okay, so this is your DH parameter. Now, if i have the kinematics while placing all the frames, as I have said, d2 can be taken as 0 if you put it like that. So, that is what I meant here.

## Placing the third frame: Attached to link 3



- $d_3$: measured along $z_2$ between $x_2$ and $x_3$
  $d_3 = -d_2$ *if second case of frame was chosen for link 2!!*
- $\theta_3$: joint angle, measured between $x_2$ and $x_3$
- $a_3$: measured along $x_3$ between $z_2$ and $z_3$
- $\alpha_3 = 90^\circ$: measured along $x_3$, $z_2 \to z_3$

Table: DH Parameters

| Link ($i$) | $d_i$ | $\theta_i^*$ | $a_i$ | $\alpha_i$ |
|---|---|---|---|---|
| 1 | $d_1$ | $\theta_1$ | $a_1$ | $90^\circ$ |
| 2 | 0 | $\theta_2$ | $a_2$ | $0^\circ$ |
| 3 | $d_3 = 0$ | $\theta_3$ | $a_3$ | $90^\circ$ |

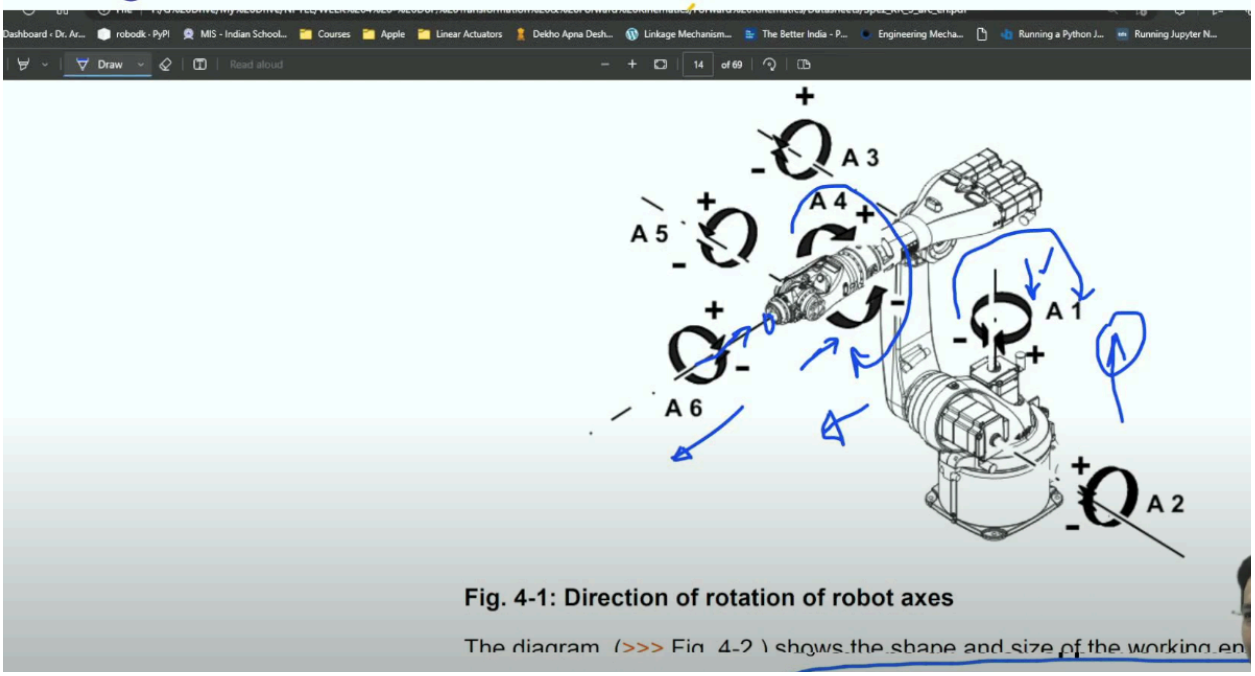
- $z_3$: along axis of rotation of link 4
- $x_3$: common normal to $z_2$ and $z_3$
- $y_3$: As per right-handed coordinate system.

NOTE: Frame placed at the end (at physical joint) in the second case is displaced along $y_2$ is wrong.
**$z_3$ can be directed opposite as well !!!**

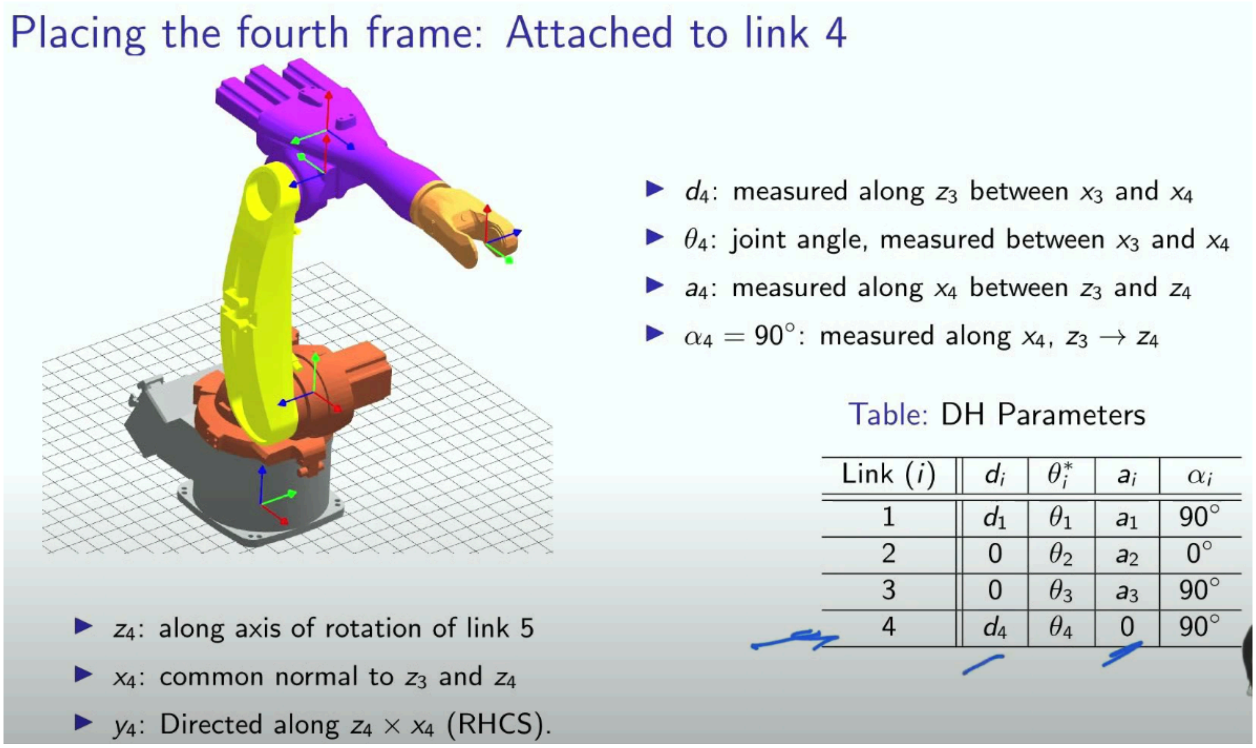
So, let us move ahead. So, now, putting the third leaf. Now I have put the third link. Okay, see what is to be done. Now, your robot. You know you already have fitted your link like this. Now your fourth link is able to move like this. Okay, so this is your this. This can move like this. So, fourth axis: actually the frame sets here, but it can be anywhere along this line. Okay, why not conveniently put it here so that it gives you the same Effie?Ct, see, is the consequence of putting it in two different locations. So, I know the next leaf, which is here, the next link that comes next, is going to rotate something like this. Okay, so I have started moving it from here, conveniently placing my frame somewhere over here. So, let us just begin. So, z3 along the axis of link 4. So, link four that comes next, okay, which is going to rotate like this. So, it is along the axis. So, this is your z three. Okay, so that will rotate. Your link four got it. So, that is your z3.

So, that is conveniently put here. This was your zero, this was your one, this was your two, this is yours. That I have placed just now. Okay, now, x3 is common normal to z2 and z3. X3 is common normal to z2 and z3. See how it can be placed now. So, this is it. So, now there exists the common normal. So, if this is your z2, you know, and this is your z3, common normal does exist. So, this becomes your x3, so this becomes your x3. This is the point of intersection. That is your frame three. So, this is very, very easy to understand in that.Case, it can conveniently be placed here. That would be wrong also. So, I'll tell you as it comes. So, y3 is, as per the right-handed coordinate system, I have placed y3, just like this one, okay, and then d3 is measured. D3, that is, the offset measured along z2 between x2 and x3. Now find out where is your x2 and x3. So, this is your x2, again x3. Both are in the same direction. So, d3 is measured along z2. Where is your z2? Zero, this was one, this was two. So, this was your z2, okay, and this was your z3. So, there is no distance. There is no offset along that side. You see, okay, there is no offset. That is the beauty of why we have put my frame, the initial frame, here, because the next frame that I am going to put in is going to be here. So, this was my second frame, so this is your third frame. Both are one over the other, so there is no d3. Otherwise, if you had taken it somewhere over here, over here, okay, you would see this distance as minus d2, as because we have taken it here, inside the robot, okay, so I don't see any distance here. So, that is again the second benefit of it. So, that is there, okay now. Theta 3 is the joint angle measured between x2 and x3. That is the joint angle. So, you know that. So, it is going to move something like this. Okay, so that is when that will be angled between x2 and x3. So, if this is your x2, you see you have x2 here, and x3 is also aligned on top of it, so both the frames are here and here, you know. So, currently, this angle is zero degrees, but if it, if this links, this link moves, you see there is some angle. Theta 3 that will come. Okay, a3 is measured along x3. A3 is measured along x3, between z2 and z3. But you see z2 is like this, z3 is like this. So, this is the distance, so there is a distance over here. So, that becomes your a3. That is the link length, because that is measured along x3. So, this was your x3. So, this is your distance, which is a3. What it? There is no d3, but there is a3. Theta 3 is there. Okay, now look at alpha 3. Alpha 3, so that is measured along x3. So, you see, you have x, which is like this. You have x, which is l.Ike this, which is like this: to take z2 to z3, now see where is your z2, this is your z2. You have z3, which is here, so you have to measure it like this: this becomes your alpha. So, from here to here, that is 90 degrees. If you rotate like this in the positive direction, about the x-axis, it is plus 90 degrees. Take z2 to z3, so alpha 3 is 90 degrees. Now, the do parameter is this one. This row has been added. Now d3 is equal to 0, theta 3, a3 and 90 degrees done, okay. Okay, now the frame placed at the end, at the physical joint, in the second case, as shown here, is displaced along y2. Okay, it is displaced along y2. So, y2, where is your y2? So this was your y2. So, if this frame is displaced along y2, it will be wrong. You won't be able to find out the parameters. So, that would be wrong. So, taking that will create this issue later on. So, you don't have to take that. And z3 can be directly opposite as well. z3 can be directed opposite as well. So, if you have taken z3 like this, okay, it can be placed. Otherwise, also, both will be the same. So, you see, DH parameters can be taken in multiple ways. At least z axis can be this way. It can be otherwise also. So, that is what is there.

# Placing the third frame: Attached to link 3




Even in the case of the datasheet of this robot, it shows, you see, the way we have taken. The datasheet says something else. So, you see, initially, we took z axis vertically upward, but in the datasheet, it shows this direction as positive. That means it is in the plane of the ground. Okay, so this is as per the datasheet. But we took it like this because I find it is very easy to understand if you take a positive direction upward to the ground. Okay, again, axis 4. You just see this is showing direction, something like this: okay, so this is your direction. So, that means it is something like inside. But we took it like this. So, again, in the end, you will find a similar problem which is here that takes an effective frame, which is something like this okay, but I prefer it taking forward as positive so that it is very, very intuitive and easy to understand. Doesn't matter. Things will take you to the same place at the end. So, be with it, need not worry about what the datasheet shows, but you have to be very careful when you convert the parameters which are shown by the robots' teach pendant. While you convert that angle, you just have to make it positive or negative accordingly and put it into your days' parameter table.

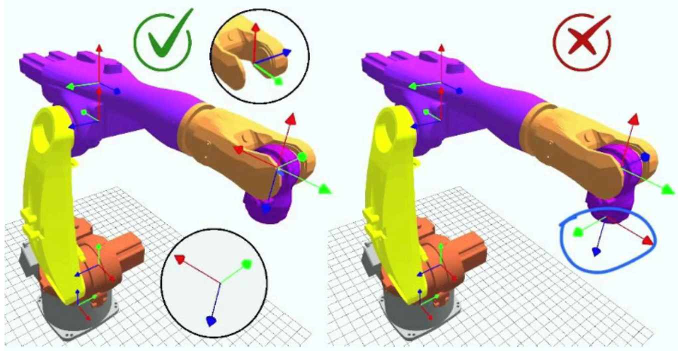



Now, moving ahead, attaching the link forward, so this is your link four, and I have to put now axis here. So, this was your 0, this is your 1, this was your 2. You have already placed the third one. Now you have to put the fourth frame that is at the end of link 4. Okay, so I am talking about this. So, how should it be placed? So, z4 is along the axis of rotation of link 5, link 5. So, you know, link 5 is this one. So, this one, okay, the axis is something like this: this was your z3, so this is your z4. So, x4 is common normal to z3 and z4. So, this is your green one. That is the y-axis. This is your z-axis. This is z4, common, normal, to z3, and z4 is x4, and z cross axis y. So, this becomes your y4, got it. So, this is how it is placed at the centre of the wrist.

Now, moving ahead. So, d4 is the distance measured along z3, the distance measured along z3, between x3 and x4. Now let us find out where is x3 and x4. Here is your x4, this is your x3, so the distance measured along them will be d4, which is measured along z3. So, you know, your z3 was something like this, so this was your z3, so this becomes your d4, got it? So, this is the distance measured along z3 between x3 and x4 that is d4. Got it.

Now, theta4 is the joint angle. That is the joint variable measured between x3 and x4. So, this is your x3, this is your x4. The angle between them will be the joint angle. That is the variable. Now, a4 is measured along x4, between z3 and z4. So, where is your z3? First, this is your z3. Where is your z4? This is your z4. Okay, so the distance between these two z's measured along x4. So, where is your x4? So this is your x4. So, there is no distance between them. So, that is making a4 equal to zero, got it. Now, Alpha 4: alpha four is measured along x4, measured along x4. So, this is your x4 angle between z3 and z4 again. This is yours, z3. This is your z4, okay, so you see, you have to be in the right-hand thumb rule, so it should be plus 90 degrees, which is coming. This is your angle, which is 90 degrees. So, alpha 4 is 90 degrees. Completing that, we'll get this parameter. You see, this becomes equal to 0, d4, theta 4 and 90 degrees done.

## Placing the fifth frame: Attached to link 5



- $d_5 = 0$: measured along $z_4$ between $x_4$ and $x_5$
- $\theta_5$: joint angle, measured between $x_4$ and $x_5$
- $a_4 = 0$: measured along $x_5$ between $z_4$ and $z_5$
- $\alpha_4 = 90^\circ$: measured along $x_5$, $z_4 \rightarrow z_5$

Table: DH Parameters

| Link ($i$) | $d_i$ | $\theta_i^*$ | $a_i$ | $\alpha_i$ |
|---|---|---|---|---|
| 1 | $d_1$ | $\theta_1$ | $a_1$ | $90^\circ$ |
| 2 | 0 | $\theta_2$ | $a_2$ | $0^\circ$ |
| 3 | 0 | $\theta_3$ | $a_3$ | $90^\circ$ |
| 4 | $d_4$ | $\theta_4$ | 0 | $90^\circ$ |
| 5 | $d_5 = 0$ | $\theta_5$ | 0 | $90^\circ$ |

- $z_5$: along axis of rotation of link 6
- $x_5$: common normal to $z_4$ and $z_5$
  $x_i$ **has to be common normal to** $z_{i-1}$ **and** $z_i$**!**
- $y_5$: Directed along $z_5 \times x_5$ (RHCS).

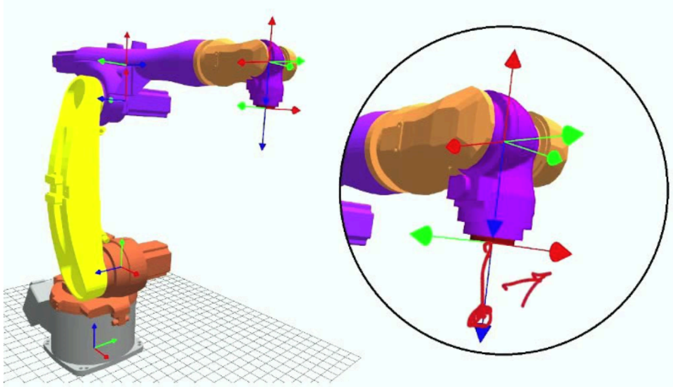
NOTE: Frame placed as in seco… s ambiguous: makes $a_5 = 0$ and d…

Now, let us put the fifth pane that is attached to link five at the end. So, z5 will be placed along the axis of rotation. That will rotate link 6. So, we'll quickly put it. We know that was a small link. That is here. You know, this is the small link which is at the end of this link, at the end. This is the sixth link. Okay, so we'll put it like this. So, this becomes your axis of rotation. This is z5. Okay, and x5 will be common normal to z4 and z5. Got it. So, where was your z4? So, this is your z4, got it? So, that was rotating your link, and where is your z5? Here is your red. This is your z5. Okay, so that is also there in this one, but because it is very clumsy out there, I use this one.

So, yes, this is your z5, and this is your z4. So, now there is a common normal that you can draw outward like this, or you can draw a common normal inward for no particular reason. So, here it is. I have put it like this. So, this is your axis, that is your x 5. So, you have z-five here. You have x 5 here. So, z cross x should give you y5, and this is not over here. It is actually sitting somewhere inside at the risk centre point. It is over here. Got it? y5 is directed along the cross-product of z5 and x5. So, that is as per the right-handed coordinate system. You can quickly place. So, d5 is equal to 0. Why? That is measured along z4, between x5 and x4. Got it? x4 and x 5. So, this was your x4, which is already here, and x5 is also there. Both are at the same location. So, that is what makes d5 equal to 0. What itself? Because there is no distance that is measured along z4. Okay, again, theta5 is the joint angle that is measured between x4 and x5. What is there? So you have already x5, you have x4, x4 over here. So, there is already some angle which is rotated, which is shown here in this figure, and anyway, theta 5 is a joint variable. You don't need to put it, and it can be put just like a variable, theta5. So, m 4 is again equal to 0. Why? Because both the location of frames are at the same location. So, measured along x5, between z4 and z5, so there is no distance between z4 and z5, got it? So this was your initial z4,

and this is your z5. So, there is no distance between them, which is measured along x5. This is your x 5, got it? So there is no distance.
So, that makes a four equal to 0. So, finally, you have to find out alpha 4. Where is it, and how is it? So, it is measured along x5, measured along x5. Let us first quickly draw: where is x5? x5 is here x5, actually. Actually, it is placed inside over here, and it is angled between z4 and z5. So, where is z4? This is your z4, z4 and z5 is like this Z5. So, you have to rotate by an angle of 90 degrees in order to come from z 4 to z 5. So, that makes alpha equal to 90 degrees, got it? So finally, if I put them all together over here in this table, this makes d 5 equal to 0. Theta 5 is the joint variable. ai is equal to 0, which is the link length, and alpha is 90 degrees. That makes it complete, got it? So my net is to be placed as in the second case is ambiguous. This makes it quite ambiguous. You have to put the frame exactly at the risk centre point to understand it thoroughly. The risk centre point should make all the axes intersect at the same place, and that forms the basis for rotating the link 6. So, I have put it conveniently there. So, anyway, that also will make a5 and d5 equal to 0. That is not an issue.

## Placing the sixth frame: Attached to the last link 6



- $d_6$: measured along $z_5$ between $x_5$ and $x_6$
- $\theta_6$: joint angle, measured between $x_5$ and $x_6$
- $a_4 = 0$: measured along $x_6$ between $z_5$ and $z_6$
- $\alpha_4 = 0^\circ$: measured along $x_6$, $z_5 \to z_6$

Table: DH Parameters

| Link ($i$) | $d_i$ | $\theta_i^*$ | $a_i$ | $\alpha_i$ |
|---|---|---|---|---|
| 1 | $d_1$ | $\theta_1$ | $a_1$ | $90^\circ$ |
| 2 | 0 | $\theta_2$ | $a_2$ | $0^\circ$ |
| 3 | 0 | $\theta_3$ | $a_3$ | $90^\circ$ |
| 4 | $d_4$ | $\theta_4$ | 0 | $90^\circ$ |
| 5 | 0 | $\theta_5$ | 0 | $90^\circ$ |
| 6 | $d_6$ | $\theta_6$ | 0 | $0^\circ$ |

- $z_6$: Assigned along $z_5$
- $x_6$: common normal to $z_5$ and $z_6$, making $a_6 = 0$
- Last frame includes the robot's tool flange in $d_6$.
- $y_6$: Directed along $z_6 \times x_6$ (RHCS).

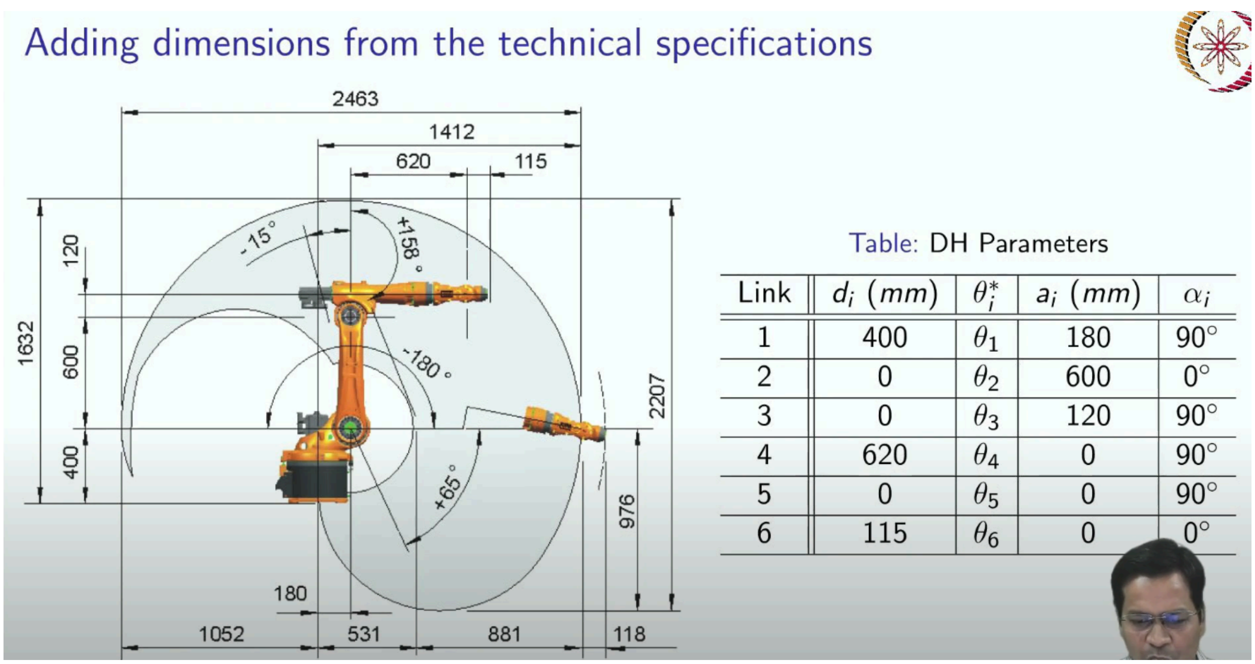
NOTE: An additional *General Tool Frame Transformation* is added to give end-effector pose.

So, yes, now the final frame. Final frame: you know it is to be placed at the end of the final link. So, here is the sixth link. So, this becomes the sixth frame. So, without doing much of an exercise, I simply dislocate the fifth frame that I have put. So, just put this fifth plane, just make some offset and bring it to that place. So, that is what we have been doing. So, if z6 is assigned along the axis of rotation of the sixth link, the sixth link is already here. The sixth link is a very small one. You see, it's just a disc. So, that is what is going to rotate, assigned exactly along z 5. Just bring it downward because that moves in this direction only. Okay, x6 is common normal to z5 and z6. Now, your x, so this is your z5, so this is your z5. This is your z 6. So, the common normal is making this x6. So, this is your x6. The last frame includes the robot's two flanges. In d

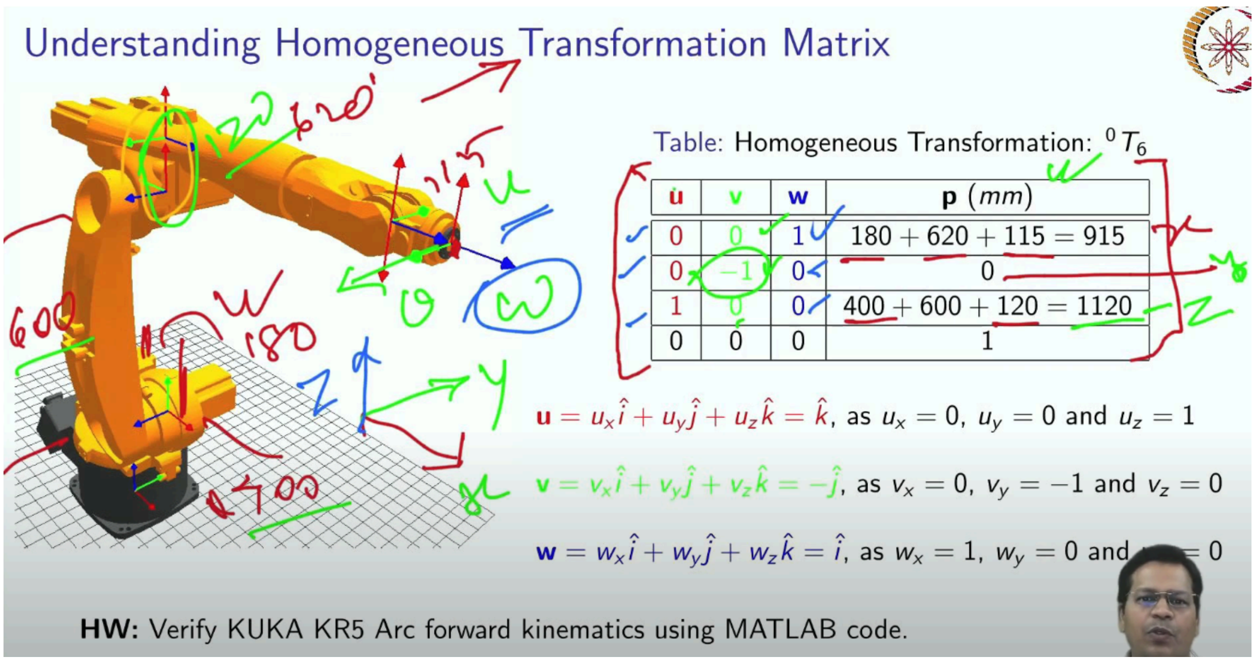
6, you see, there is an offset. Offset, you have to travel along z axis. So, that is capturing the distance. That is d 6, which is here from this point to this point. So, that is a small distance captured here, that is to be captured. You should not end your robot's frame right at the centre point. You should bring it to the tip of the rotor robot so that you can ultimately, when you go forward, kinematics you will get the end vector position, not any intermediate position. Okay, y six is directed as per the right-handed coordinate system. So, d 6 is measured between x 5 and s 6. So, as we did just now, x 5 and x 6. Here is your x 5. This is your x 6, distance between them is measured along z 5. So, this is your z5, got it?

Theta 6 is the joint variable that is measured between x5 and x6. That is the joint variable. So, forget it. That is just a parameter, which is a variable. a4 is equal to 0 because it is exactly in the same line. So, there is no offset between z5 and z6 measured along x 6. So, that makes a4 equal to 0. Alpha 4 is equal to 0. Again, it is measured along x 6, going from z 5 to z 6. Z 5 and z 6: both are in the same line, so there is no angle between them.

There is no twist for the sixth link, so that is exactly making alpha4 equal to 0. Now, the DH parameter table is complete. I have put all the variables here and this makes it complete. So, an additional tool frame transformation. So, at times, you have an additional tool frame. So, sometimes maybe you have a link which is coming even after this. You can put a frame directly over here instead of putting it at the tip of the plans. Okay, so that will give you the end effector pose. So, that distance also you can already take into consideration while making your DH parameter. But normally, when the robot is delivered, it is delivered like this, and it is quite okay.




Now, let us populate this DH parameter table using the technical specifications which are given in the manual. So, you have just to put the distances as it is given in the datasheet. So, I'll just copy them from here. So, you see, it is 400 that is the offset. Offset from this point to this point. So, you see, it is 400. Now, theta 1 is the joint variable: 180, which is the distance between this and this going from this distance. So, this distance is 180. Alpha is from the DH parameter table. This was 0, now 600. 600 is the distance between this and this. So, that was making it 600. That is the distance between the two z-axis, and again 120. This is the distance. This one, you see, okay, 620 is here. That is from the risk centre point to the frame which was placed here. So, that is the distance. It was measured around z axis. That makes it an offset, joint offset, not the link length. The link length was 0. The 5th one both were 0. The 6th one is distance, which is here. So, that is taking it to the plan step centre. Okay, so that is 115. So, that is here. So, that comes here. So, you got it so you can directly create the DH parameter table in terms of variables and later on, you can put it the way exactly as it is in the technical specifications of the manual, or, if possible, you can measure it. That is fine, but that will be quite inaccurate, so this is it.




So, this is how you have to do forward kinematics. At least for this position, if you do forward kinematics, you will see you are getting a homogeneous transformation matrix, which is like this. So, you can verify this using one of the situations instead of verifying the end effector poses for position and orientation. It is easy to take it to a position where you can directly calculate using the parameters which are given in the robot's manual. So, you know the link lengths. You took it to a position where you can directly calculate your end effector position and see whether your forward kinematics is also giving you the same result.

So, at least for this one, I have known it is distance which is 180 plus 620 plus 115. So, this was 115, this was 620, and from this to this distance, you know, it was already 180. So, the total distance which is here is x, like this, and then about y, because in this particular position, y is coming out to be zero, but if you rotate its axis one by 90 degrees. This force will go in this direction, and in that case, it will become the same. 915 will be visible along the y-axis, not along the x-axis. Okay, in that case x will become equal to zero. Got it? So now take the height. That is z. So, it is 400. That is the distance from ground level to this level. So, that was 400. 600

was the link length from here to here. That was 600. Now, 120. 120 is from this distance. So, this was your 120, so that is your 120. So, 400 plus 600 plus 120, it comes out to be 1120. So, that is what is the z location. Okay, so that is your z. This is your y. Got it so correctly?
You can verify your position, at least for two standard positions where you can easily calculate manually. Also, okay, orientation can be seen, at least in this course, where it is now. You see, u is the projection of u, that is this frame, this is your u, this is your v, and this is your w. So, projection of u along x, along x. it is. So, where is your x? This was your x, right? So, you have your x, y, and this is your z. So, just compare how is your u, v and w oriented with respect to x, y, z. So, this is exactly the orientation matrix. So, at least for u, you see, it is coming out to be 0, 0, 1 because u is now directed along the positive z direction, you see. So, exactly, it will be 1. Similarly, v, v will be. V is in this direction, you see. Okay, so v comes out to be 0 minus 1, 0. Why, along x, it has 0; along y, it is directed opposite. So, it is minus 1, and finally, along z, it is 0. Now, finally, it's w. w is as it is, so u, v and w. w is like this. w is pointing directly towards x, so it becomes 1, and rest two will be 0. So, one of them, if it comes, one remaining will automatically be 0 because it is a unit vector that can be 100 per cent along one direction than it is in another direction. It will be 0.

So, that's all for this. Try to verify these forward kinematics using your own Matlab code or maybe any programming language you are familiar with. So, that's all for this. Thanks a lot. So, in the next class, we'll be doing inverse kinematics and differential motion analysis. That is the module that we will be starting. That's all for today. Let me say thank you this way. So, we are done with industrial robot forward kinematics. It is what at least you also can think of generating in your programming language, maybe Matlab or python or c, whatever you are familiar with. That's all. Thanks a lot.