NPTEL Online Certification Courses
Industrial Robotics: Theories for Implementation
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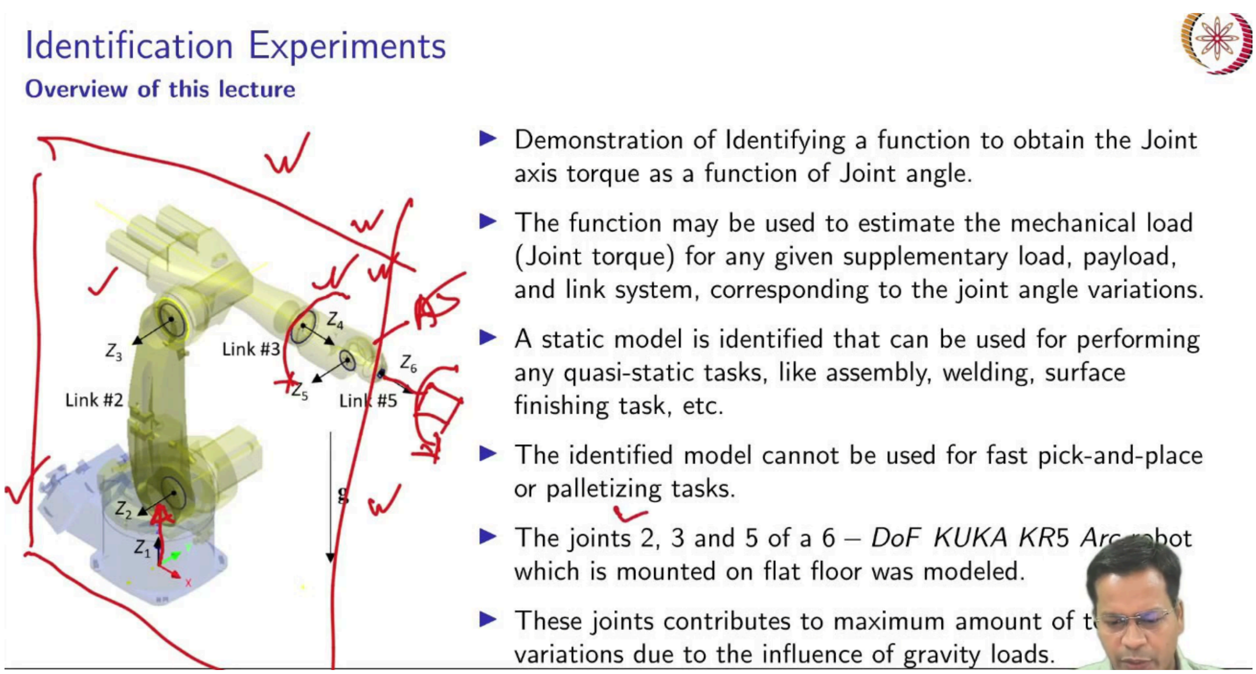
Week: 10
Lecture 41

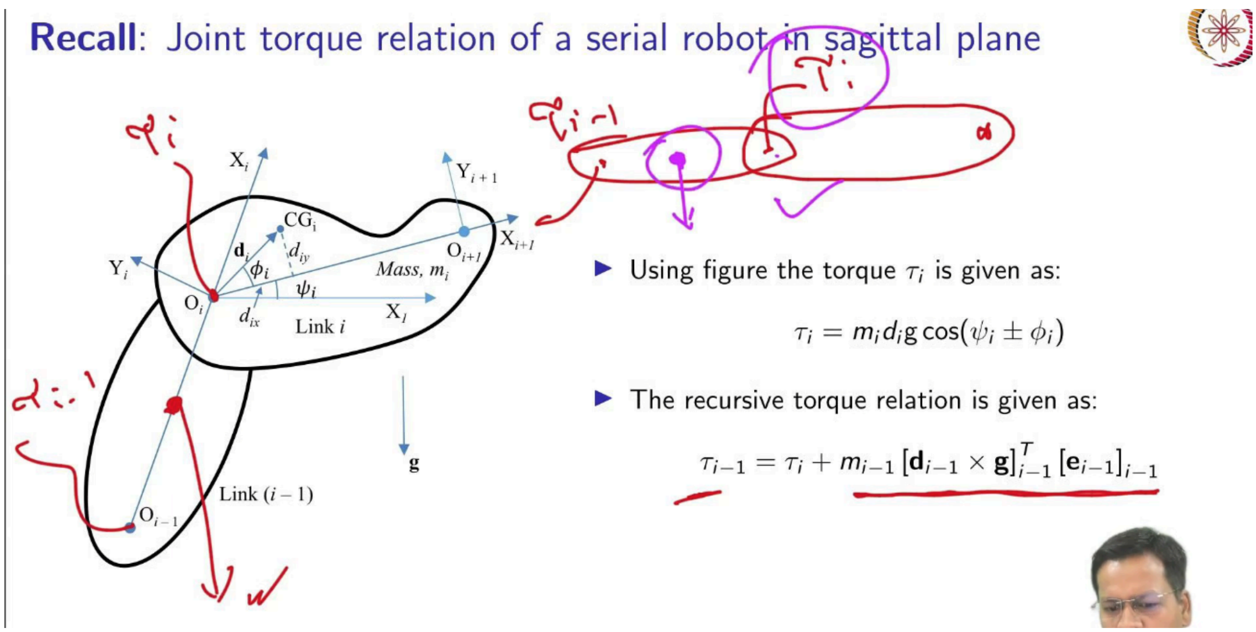
Identification Experiments

Hi. So, in the last class, you saw how important a load is for a router. So, today, we will do one such experiment as a case study. I am just covering that in this lecture, where I will be explaining to you how a robot actually identifies such loads which are placed on top of the robot. In the last class you saw how a robot can identify that itself through some software plugins which are there in the robot controller. So, today, we will just take up a small example when I try to determine some static loads which are placed on the robot, not exactly the loads which are placed, but rather the complete load which is combined with the added load and the link. The moment that is going to come at the joint due to that will be determined.



So, let us continue with today's class. So, this is just an overview of today's lecture. So, I will be demonstrating the identification of a function to obtain the joint axis torque as a function of Joint angle. So, this is only the mechanical load that will be determined. So, your electrical load will just be a function of the load, that is, the mechanical load itself. So, we won't talk much about the electrical load that is going to come on the actuator as of this lecture. So, yes, the function may be used to estimate the mechanical load, that is, the Joint torque, for any given supplementary load, payload and the link system. It includes everything which is there, including the wires, if it is there, or solenoid valves or a transformer, whatever is there corresponding to the Joint angle variation. So, joint torque corresponds to the Joint angle variation. We will try to figure out that. The static model is identified that can be used for performing any quasi-static task. A quasi-static task is a very slow-moving task. The robot performs normally like an assembly task. You do move your end-effector with very small motions, maybe micro motions also, but yes, the robot does the task. It is as good as considering that robot to be static. So, not much of dynamic torques are going to come at the joints. So, assembly tasks welding tasks, if it is welding very slow manner, then can also be considered to be quasi-static task-grinding, polishing, and buffing. They are all quasi-static tasks in which the robot constantly maintains a force normal to the surface. So, it is continuously making contact and that motion of the robot is considered very, very slow. So, that also is a quasi-static task. So, a static model is identified that can be used for performing that quasi-static task. So, this is today's lecture. I am going to discuss something that we have done in our lab and how such model identification is going to help you to do the load calibration thing that we discussed in the last class. So, the identified model cannot be used for fast pick-and-place tasks such as palletising tasks. That normally is performed at very high speed by any industrial robot. So, this lecture will be covering only joints, which are two: that is, the second joint, which is here, the third joint and the fifth joint, which is there. So, torque, I will be identifying the torques which are going to come on, these three only. I am doing it for 6 degrees of freedom KUKA KR 5 Arc robot, which is mounted on a flat floor. It is not mounted on the wall on an inclined plane or a ceiling, and it is on the flat floor. That is what I am assuming. This contributes to the maximum amount of torque variation due to the influence of gravity load. So, you see, at least with axis 4, z4, that is shown here in this figure, you see if this is rotating, and you have a load which is fixed somewhere over here because the load rotates almost along its axis, there is hardly any torque variation which is created at any of the joints because of its motion. Because of this motion It will have some effect on axis 5. If it is rotating, that torque will cyclically change in a sinusoidal manner. That is fine. But the variation that is over here, and over here, over here is almost minimal, So yes, I am not considering any z4-axis torque. Also, I am not considering the torque which is going to come over here. That is z1.

You see, it is parallel to g if I move the robot anywhere in this sagittal plane. The sagittal plane is the plane which passes through all the axes together. So, this is a plane like this one. The whole of the robot, at one instant of time, can lie in that sagittal plane. It becomes a planar robot. Everything works on that plane. Suppose it is moving in this plane. So, there won't be any torque that is going to come because of those motions on axis 1 also. So, this is a sagittal plane motion. So, the joints that I am considering are joint 2, joint 3 and joint 5, only of a 6-degree of freedom KUKA KR5 Arc robot.



So, let us move. So, let me just recall some fundamentals here. That is the joint torque relation of a serial robot in a sagittal plane. So, these are the two links that I am considering. This is the link (i-1), and this is your link i. In this figure, you see, torque i may be given as tau i, this is a scalar value-is mi, mi is the mass of this link ith link, g is the acceleration due to gravity.

$$\tau_i = m_i d_i g$$

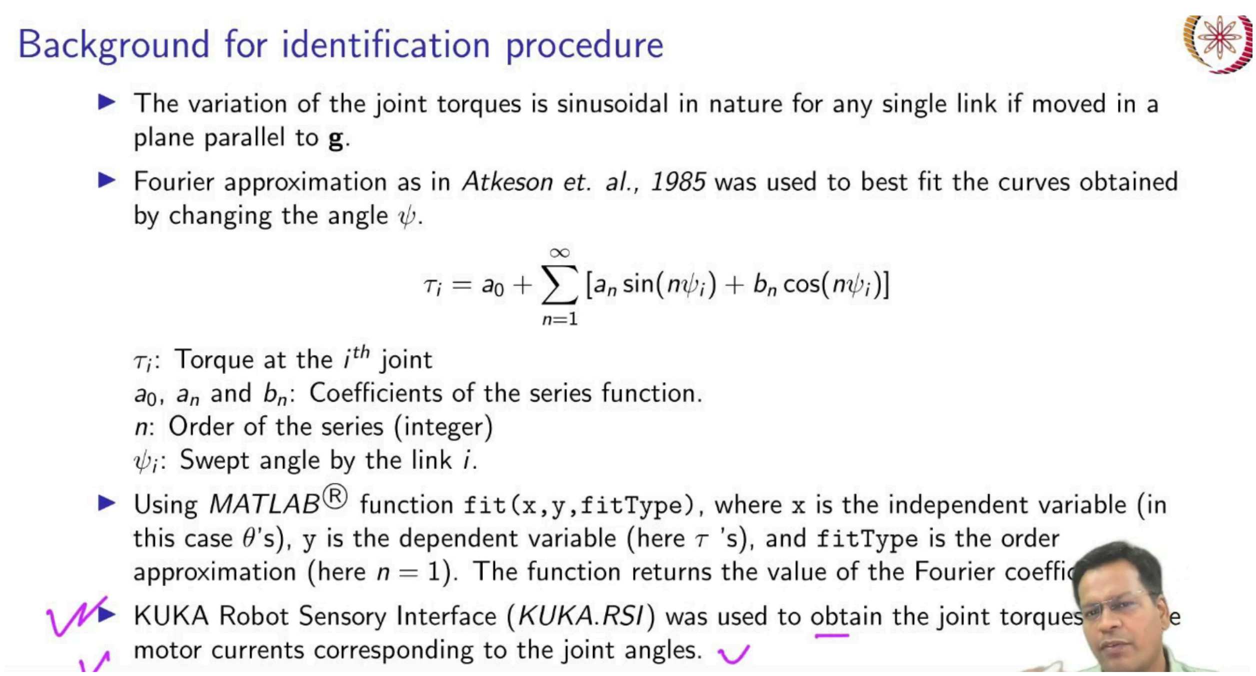
So, that is the force which is acting. mig is the force acting downwards, and this is your centre of gravity location here and you have a vector given by di that connects the axis of rotation to the centre of gravity location. This vector is in the plane. So, if I connect two axes, O_i and O_i plus 1, you see there are two angles. So, psi i is the angle which is defined, and that is fixed for the centre of gravity location referred along Oi, Oi plus 1, with reference to Oi, Oi plus 1. So, this psi I, that is a constant. So, di has two projections, d_{ix} and d_{iy}. These two projections are not going to change because the centre of gravity location is not going to change if it is referred with respect to the oi frame, with axis Xi+1 Yi plus 1, all defined. So, if it is referred with this plane, it is fixed. So, d_{ix} and d_{iy} are not going to change. Now, there is another angle, that is ψi. So, this is the effective angle with which this link is going to rotate. So, this is, and this is the horizontal reference frame. So, this is perpendicular to the g direction. So, this is there. So, this is the angle which is measured with this horizontal reference frame, not necessarily the Joint angle. A Joint angle is something else, so it is Joint angle is basically the angle between Xi and Xi plus 1, measured in this plane. So, that is not what I am going to consider now. So, I have just taken ψi, which is measured within this plane and from this horizontal axis, Xl. So, this is your angle, and this is your line, which is making some angle with this. This is the horizontal line. So, you can now see this clearly. So, this is your angle. So, effectively, taui is equal to midig cos, ψi plus phi i.

$$\tau_i = m_i d_i g cos(\psi_i \pm \phi_i)$$

Let me just clean it up once again. So, now you can see this very, very clearly. So, this is your angle, this angle plus this angle. The sum of that is this angle. So, that is shown here. So, you have two projections of di, that is, along x and along y, and because of that, di cosine. So, this is your distance, so it is over here. So, this is the effective arm on which mig is acting. So, di cos ψi plus phi i into mig, so that is the effective torque that is along this axis. So, that is Tau i. So, this is the first thing, and the next one is the recursive torque relation is given as tau i minus 1.

$$\tau_{i-1} = \tau_i + m_{i-1}[d_{i-1} \times g]^T_{i-1}[e_{i-1}]_{i-1}$$

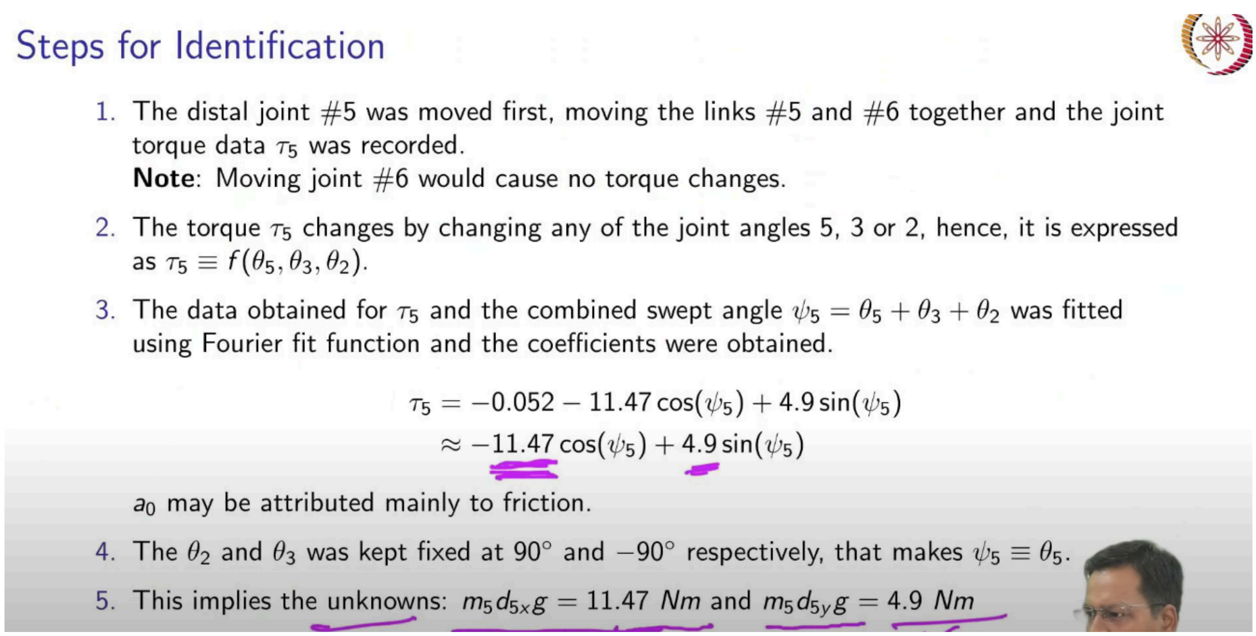
So, whatever you see over here, tau i minus 1 is because of the torque, which is here already. So, this is your tau i, and this is your tau i minus 1, the sum of whatever torque that is going to come because of the centre of gravity, torque which is created due to the centre of gravity, of this. So, that is the torque, that is the additional torque. So, you see, if you have a link which is here, if you have another link which comes here, if you want to calculate tau i minus 1, and there is already tau i over here. So, torque over here will be the sum of torque which is here and torque which is caused due to the pull which is on this link itself. So, torque, which is here plus torque due to this, is the total torque that comes over here. So, that is what is stated vectorally out here. So, this is already covered earlier in our robotic statics also. So, these are the two fundamental things that you should just recall.



So, now let us move. How to do this identification procedure? So, the variation of torque is sinusoidal in nature. You have seen just now for any single link if it is moved in a plane parallel to g. So, this is what we have seen just now. Next, the Fourier approximation, as given by Atkeson et al., 1985, was used to fit the curves, which are obtained by changing the angle psi i. So, if you change this angle, the angle which is here. You see if you change this angle, you can only change this angle. You cannot change this. This is fixed. So, when this link is making any motion, that is what is shown here. So, if that variation is there, torque will change like this.

$$\tau_i = a_0 + \sum_{n=1}^{\infty}[a_n sin(n\psi_i) + b_n cos(n\psi_i)]$$

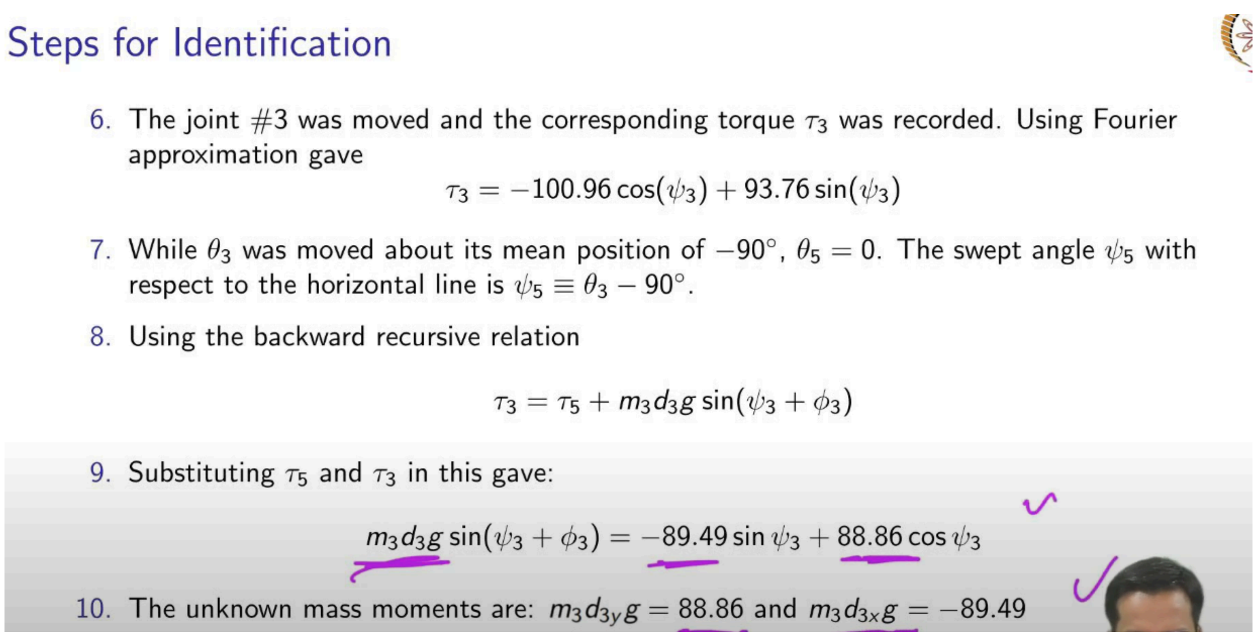
This is a constant. So, torque at with joint is given by this. a0 an and bn are the coefficients of the series function. This is effectively a series. Normally, we see only the first order. That is what appears in our previous equation. n is the order of this series, which is an integer, and psi i is the swept angle by this link i. So, this is the model we are considering. We will be taking n is equal to 1, as you have seen in our previous equation, so that will basically converge to the previous equation if you take n is equal to 1, and I will obtain all the data, I will make the robot link move, and I will obtain the torque corresponding to the Joint angle, and I will try to fit it to this. This is what is our job and I will try to get these constants. In order to do that, I will capture all the data while moving the robot and, using the Matlab function, fit(x,y, fitType) and the type of fit I can do. So, where x is an independent variable, in this case it is theta, that is the Joint angle. y is the dependent variable over here, and it is tau, which is the joint torque, and fit type is the order of approximation. I told it should be 1 for our case. The function returns the value of Fourier coefficients. Those are an, bn and a0. You saw. Torque is a function of sine and cosine. This constant is appearing because of some sort of idle torque which is there may be because of friction. So, KUKA robot sensory interface, KUKA RSI. I am going to use the KUKA KR5 Arc robot, as I told you. So, I am going to use this add-on now that allows me to obtain the joint torques and the motor currents corresponding to the Joint angles. If I move this robot, I can use this add-on to obtain all the joint torques. Mind it, this robot doesn't have any inbuilt torque sensor at its joints, so it probably has a model of its motor which can get because you can measure the current. So, using that current effectively calculates the torque, and it gives you using KUKA RSI. So, I will be obtaining that torque, basically.



So, let me just start the identification procedure now. So, these are the steps in the first case, and I started with the last link first. I started moving the last link 5. So, link 5 and link 6 will move together. As I have told you, moving link 6 will not cause much of a change in the joint torques, so I am just excluding that. Anyway, I want to keep my robot in the sagittal plane only. So, that is why I am moving this first, and this you already know by your existing knowledge in the case of robots. So, you have to come from something that is already known in hand. So, you know everything about this. So, there is no torque which is going to come over here. That is the reason I am moving this first. If I move this, torque variation will be there, and that is only because of this link motion, and there is no torque at this end. So, that is the reason I started here first, and then iteratively I will come back. Because while moving this link I already have the torque variation at this joint. I will obtain the model of this link first. Then I will do tau i minus 1 if this is the link i so, if this is already obtained by the previous motion. This can be obtained by the motion over here and the torque which is over here, and finally this can be obtained. So, that is the reason I am moving backwards. Torque is to be calculated in a backward manner. You have seen this in the earlier examples and also earlier cases when we were doing statics. So, the torque changes by changing any of the Joint angles: 5, 3 or 2. Hence, it is expressed as tau 5. You see, torque 5 changes in the backward manner. Torque 5 is a function of theta 5, theta 3 and theta 2. For any of these, if they are changing, torque 5 is going to change, is it not? You see if you have a link which is one after the other, so any of these, if it is changed, if you change this, you are going to see some change over here. This is your torque 5. So, even if this is moving, this is going to change. If this is moving, this is going to change. Any of the prior links also, if it is moving, this is going to change. This torque will vary because, effectively, the whole of this link is moving with respect to the g direction. So, that makes this change. So, this is valid. So, tau 5 is a function of theta 5, theta 3 and theta 2. So, the data is obtained while link 5 is moving and combined swept angles. So, psi 5 is equal to theta 5, theta 3 and theta 3 sum together was fitted in this Fourier fit function, and coefficients were obtained. So, you see, once I acquired the data of tau 5 and this angle, I put them together and used the Matlab fit function to obtain the coefficients.

What I got is something like this. So, Tau 5 is equal to this. This is a0, this and this. So, these 2 are the coefficients I wanted to have. a0 may be attributed. That is because of friction. It is going to come, and it is a very less value. So, I am simply ignoring it to make it a purely sinusoidal manner. So, that is what is giving me to this. So, $-11.47\cos(\psi 5)$ and $4.9\sin(\psi 5)$ are the coefficients that I could get. Now, theta 2 and theta 3 were kept as 90 and minus 90, and this is theta 3 and 90, respectively, the way I have shown in my first figure. That is the canon position the robot was in. So, in that case, these 2 are like this. In that case, psi 5 is equal to theta 5. This is minus 90, this is plus 90. So, this becomes equal to this. Now, this implies that the unknowns are this, so effectively: the dx component comes here, and the dy component comes here. So, you saw you had 2 projections of d, and those were causing the moment at the joint, and the moment projected along the axis is the same. That is the magnitude of the axis because the robot is in a sagittal plane. So, you see, these 2 should be the same. So, m5 d 5y g is equal to 4.9, and the x component goes here. So, those 2 are the moments that are directly appearing here.

So, let me just show you that figure once again. So, you see, you have an equation which is given like this: so this basically has got 2 components. This torque has got 2 components. One is because of the component which is over here, and the next one is because of the component which is here, so dx. So, your force, mig, acts over here, and it is creating due to this distance. First, that is the first torque which is going to come, and that will be your cosine component, and this is also there this y component, and you have that force that is acting due to the mass is acting downward, that also is creating a moment over here, and those 2 combined are shown like that. So, you have 2 components, that is, midixg and midiyg components. One will be cosine, and that will be the sine component. Got it. So, now you see you got to this. So, the first motion is done. This model has been identified already. That is the top 5 model, for the motion is already identified.



Now, we are going to the third link motion. Joint 3 was moved, and corresponding joint torque T3 was recorded, and again, using Fourier Fitt approximation gave me this equation:

$$\tau_3 = -100.96\cos(\psi_3) + 93.76\sin(\psi_3)$$

This is the tau 3 equation. Now, tau 3 was moved about its mean position, that is, cannon position, if you remember. So, this is your link, this is your axis, these are your axis, and this is your thing. And this is your second link, this is your third, and this is your fifth, so now I am talking about this. So, it was in elbow position, like that. that is the cannon position. In that case, it was minus 90 degrees. So, this is your axis, and in that case, it was minus 90 degrees. Theta 5 is equal to 0, and swept angle psi 5 is with respect to the horizontal line. That will be given, as this psi 5 will be equal to theta 3 minus 90. You see, if theta 3 is equal to 0 degrees, it comes totally like this. In that case, it goes to minus 90 degrees. Is it not? So, measured with respect to the ground. You see, this is with respect to the ground, so it comes perfectly like this. So, in that case, it is minus 90 degrees. So, that is what. So, this is there. Now, using backward recursion, t3 can be written as t3 is equal to t5 and this is it not?

$$\tau_3 = \tau_5 + m_3 d_3 g \sin(\psi_3 + \phi_3)$$

So, if you see, this is your fifth link, this is your third link. Forget about fourth, because that is, we are not moving, assuming it is frozen. So, fifth and third. So, I am talking about this. So, that comes here. t5 comes here, and this is due to the link which is here, is it not? So that is what is making this. Now, substituting t3 and t5 that we have obtained. The earlier model was already identified if I substitute this and the previous t5 to these locations so that I can write this equation like this,

$$m_3 d_3 g \sin(\psi_3 + \phi_3) = -89.49 \sin\psi_3 + 88.86 \cos\psi_3$$

The same thing will come here, and this is because of the sum of t3 and t5. So, substituting all the Joint angles, I got this. Now, the unknown mass moments are in this case, and I have split this once again the way we did it for the fifth one. So, this is 88.86 that comes here, and this one should be 88.86. That is what we have done here, and this is because of this. Got it. So, this is already here. So, unknowns are identified once again.

Steps for Identification

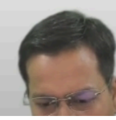
11. The torque τ_2 was recorded keeping the joint angles θ_3 and θ_5 as zeros, i.e., $\psi_2 \equiv \theta_2$. The torque τ_2 is expressed as

$$\tau_2 = -375.7 \cos \psi_2 + \tau_3$$

which gives $m_2 d_{2x} g$ as 375.7 Nm.

The identified mass-moments are now put together as:

Link i	$m_i d_{ix} g$ [Nm]	Mass Moments $m_i d_{ix}$	$m_i d_{iy} g$ [Nm]	Mass Moments $m_i d_{iy}$
5	11.47	1.169	4.90	0.499
3	89.49	8.612	88.86	9.058
2	375.70	38.297	0	0



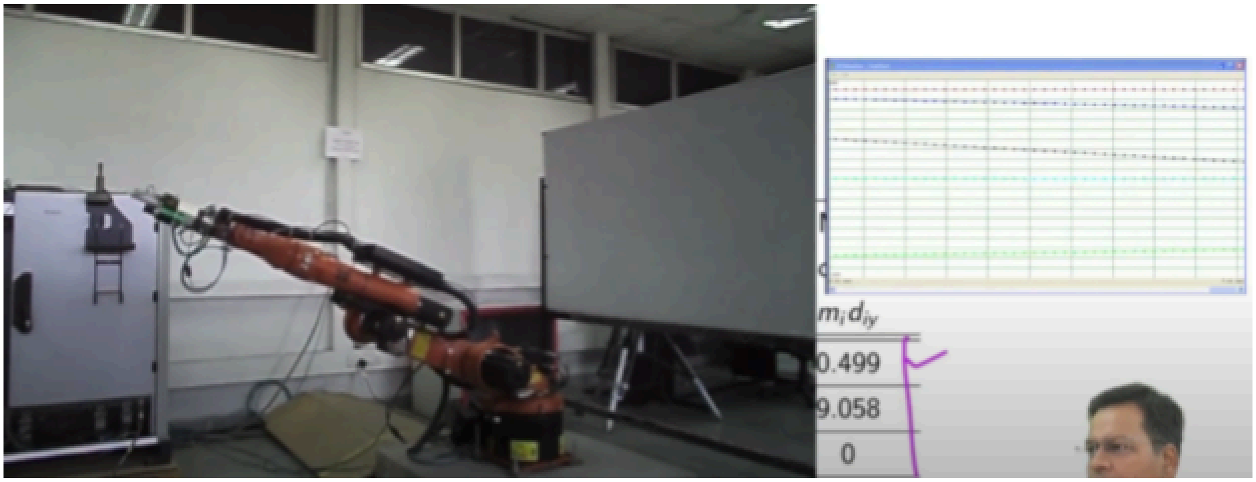
The torque 2 is now recorded. Now, I am moving joint 2, and tau 2 is recorded, keeping Joint angles, theta 3 and theta 5 as 0. In this case, psi 2 will be equal to theta 2. The torque is expressed as this:

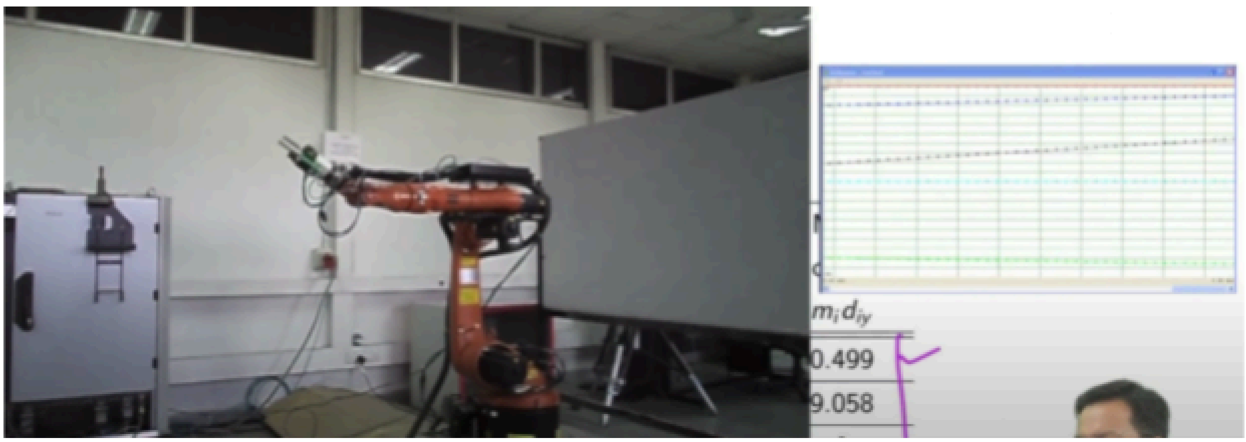
$$\tau_2 = -375.7 cos\psi_2 + \tau_3$$

Using the Fourier field, I could obtain this, and it did not have any next value or any sina value because this link was straight now, and it was symmetrical. So, hopefully, CG was lying on that axis itself, and this can iteratively be written like this: tau 2 is equal to tau 3 plus this got it, which gives unknowns, which is only along X, as this:

$m_2 d_{2x} g$ as 375.7 Nm

There is no Y offset, which is there; the centre of gravity lies in the line which connects both the joints which are here, which are here. I will show you in the figure also (slide 1). You have these 2 joints there. So, you found out this, and you see it is not at an offset. It is exactly lying on the line that connects both joints. So, that is what I am talking about, and in this case, you had some kind of shift along the Y-axis. When you were talking about this, the CG was not lying in the line that connects these two. Now, summing them all together, I have obtained mass moments for all the links and all the components I have obtained. So, putting them all together, the identified mass moments are now put together in this table like this. So, whatever values I have obtained, where these were divided by g, which was there. It gives you these values, and that is done for all the 3 links that I have moved. So, yes, now let me show you what actually is done.



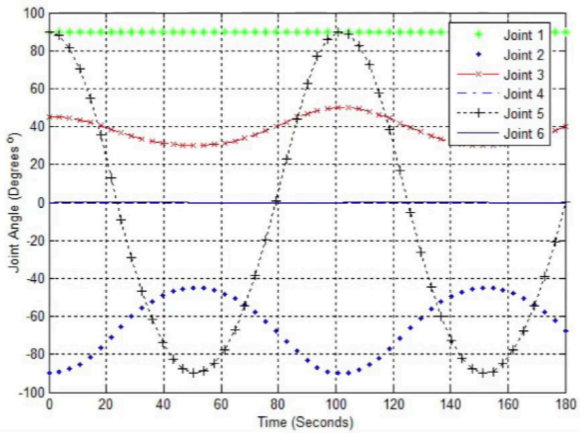


I have some videos that will demonstrate exactly what was done. So, yes, this is the experiment. This is the data. You see, on the right side of it, you see the robot. This is the axis 2, which is in motion now, and data is getting acquired on the right side of it continuously. I have acquired, using an RSI monitor over here, KUKA RSI. This is the torque which is getting captured over here. Now, axis 2 comes to rest and axis 3 starts doing that motion and now, again, the data is getting captured. All the axis joint torques are getting captured. The Joint angle is also recorded. Now, axis 5 is moving. So, these are the motions that this robot has made. Got it? So, this is how I made the robot move, acquired the data, did Fourier fit, and I could get the mass moments, which was actually responsible for doing the torque changes that you have noticed. So, using this whole of the Model is now identified, and I am using those mass moments now to test whether it can give me actual torque.

Testing of Identified Mass-Moments

Joint angles to calculate empirical torque values

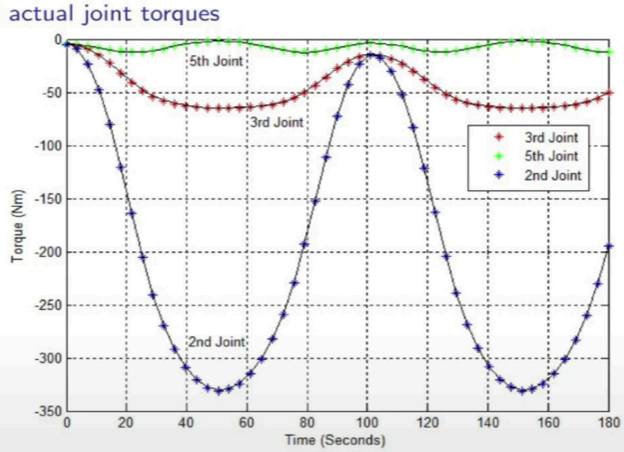
	Joint 1	Joint 2	Joint 3	Joint 4	Joint 5	Joint 6
Initial	90	−45	30	0	−90	0
Final	90	−90	50	0	90	0



So, this is the test trajectory that is, in sagittal plane motion, only without moving. Joint 4 and Joint 6. I am making some straight motions like this. This also is not moving. Also, so only this, this and this is moving. So, axis 2: I have made it move from minus 45 to minus 90. Joint 3: 30 to 50 and joint 5: minus 90 to plus 90. So, these are the variations, this is the test Joint angles. With time, that is done.

Testing of Identified Mass-Moments

Variation of estimated and actual joint torques



Note: A Similar procedure may be used to obtain the electrical loading of the motors corresponding to the joint angle variations.

This gave me torque variation like this for all the joints. So, this is for the second joint, this is for the third joint and this is for the fifth joint. So, as expected, dotted ones, what you can see here, are the predicted ones, and the continuous one, which are there, are the actual ones. So, both are exactly overlapping. You see, for this test trajectory, it closely matches, it exactly matches to this, so using this, you can predict the load which is going to come and mind, it whole of this model was identified with. All the supplementary loads are in place. If the load is there, it is already fitted. I have acquired data for that. I have identified my mass moments with that, and because it is identified with all those loads, the torque that I am going to get out of my model is exactly the torque which is going to come, not with the bare robot, but with the loads which are there. So, this will help me to identify if there is any overload, if it is there. So, this is how even robot manufacturers are able to calculate this torque, and they already have the mass moment of the link itself. They can easily segregate this added mass from the link mass. In my case, the link mass and the added mass are considered together, and I could get the mass moments. So, this is a very good demonstration of which an identification procedure you have seen exactly can tell you exactly if your link is going to be overloaded. Your joints are going to be overloaded, but yes, it is purely mechanical. A similar procedure may be used to obtain the electrical loading also for the motor, corresponding to the Joint angle variation. But you see, if the torque is higher, the current is going to be higher, so it should follow the profile which is here for the torque also. So, that is what is expected.

So, with that, I would end here. In the next class, we will do a Repeatability Test, and explicitly, I will discuss ISO 9283:1998, which is a performance test criterion that is defined in this ISO class. So, the repeatability test is one of them. So, we will discuss very much in detail for that. So, with that, we will end today. That's all. Thanks a lot.