NPTEL Online Certification Courses
Industrial Robotics: Theories for Implementation

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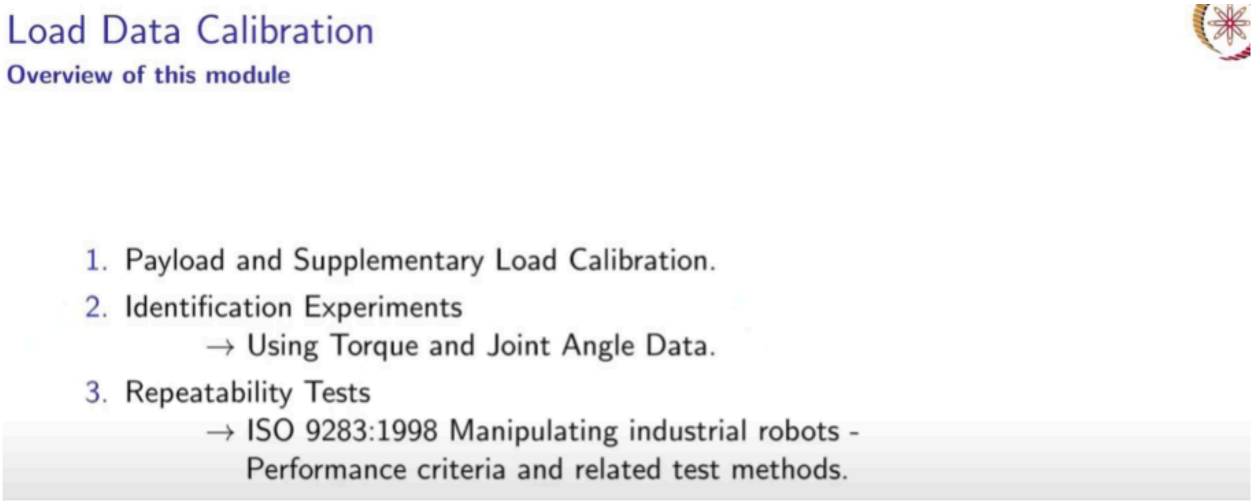
Lecture 40

Payload and Supplementary Load Calibration

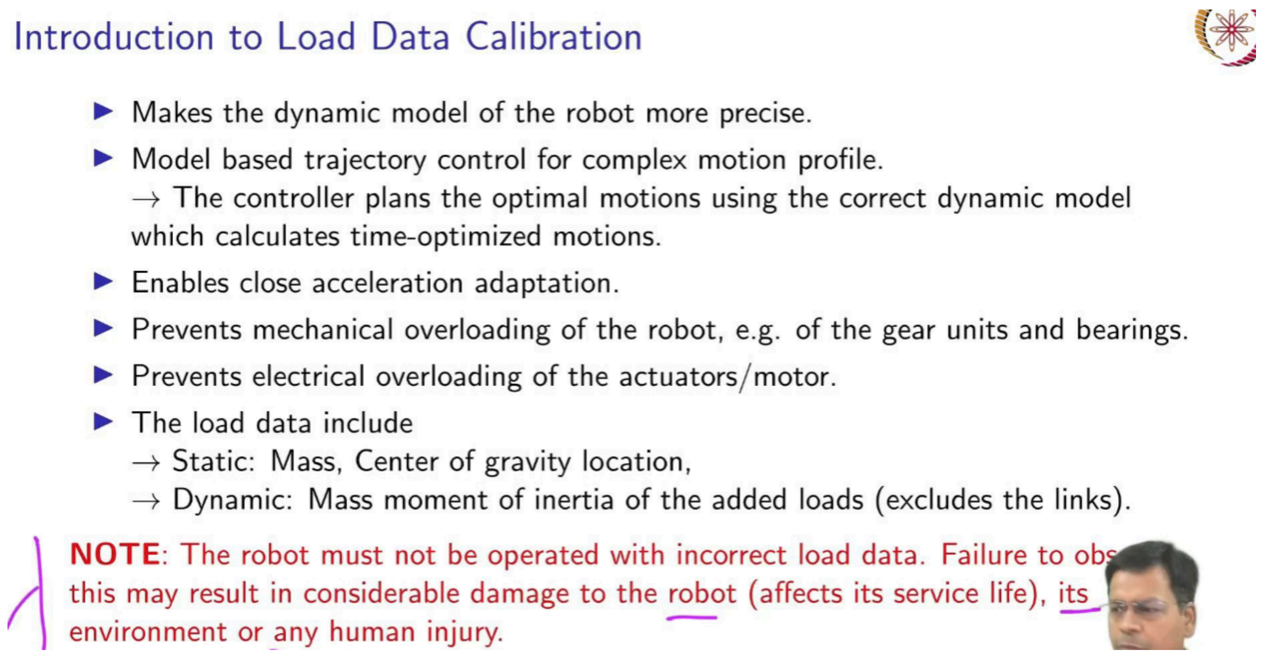
Hello, and welcome to the module load data calibration. So, in this module, we will see how important the load is for a robot, a huge robot mostly. So, by now, you have gone through dynamics in which you are already familiar with the equation of motion of a robot, and you have seen how that is a function of mass and moment of inertia. So, you have already gone through the trajectory and position control of any robot, especially for joints. You have seen how joint motion can be controlled, and you have also seen how sensitive it was for the masses which are involved and for the moment of inertia if it is there. So, in this module, we will see how the load is to be communicated to the robot itself.



Load Data Calibration
Overview of this module

1. Payload and Supplementary Load Calibration.
2. Identification Experiments
   → Using Torque and Joint Angle Data.
3. Repeatability Tests
   → ISO 9283:1998 Manipulating industrial robots - Performance criteria and related test methods.

So, let us continue with our lecture today, that is, on payload and supplementary load calibration. So, what we are going to cover in this module are payload and supplementary load calibration which is today's lecture that we are going to do and identification experiments. That is again for the same reason. We are also doing identification, also in order to identify the moments that are going to come due to any static masses, if they are there. So, that is to identify the static moments. Basically, that is only due to the slow motion of the robot. If it is making, we will do that using torque and the joint angle data by making different kinds of motion. We will see very much in detail in this and the last lecture. We will continue with the repeatability test. That is ISO 9283:1998. That is one of the most important parameters which is mentioned in the robot's specification you have seen. So, this ISO 9283:1998 standard especially deals with manipulating industrial robots. It deals with performance criteria and related test methods. We will discuss various test methods in this. What are the environmental conditions it should be there, and how the robot is to be tested for repeatability and those things. So, let us continue with payload and supplementary load calibration. That is today's lecture.



Introduction to Load Data Calibration

- Makes the dynamic model of the robot more precise.
- Model based trajectory control for complex motion profile.
  → The controller plans the optimal motions using the correct dynamic model which calculates time-optimized motions.
- Enables close acceleration adaptation.
- Prevents mechanical overloading of the robot, e.g. of the gear units and bearings.
- Prevents electrical overloading of the actuators/motor.
- The load data include
  → Static: Mass, Center of gravity location,
  → Dynamic: Mass moment of inertia of the added loads (excludes the links).

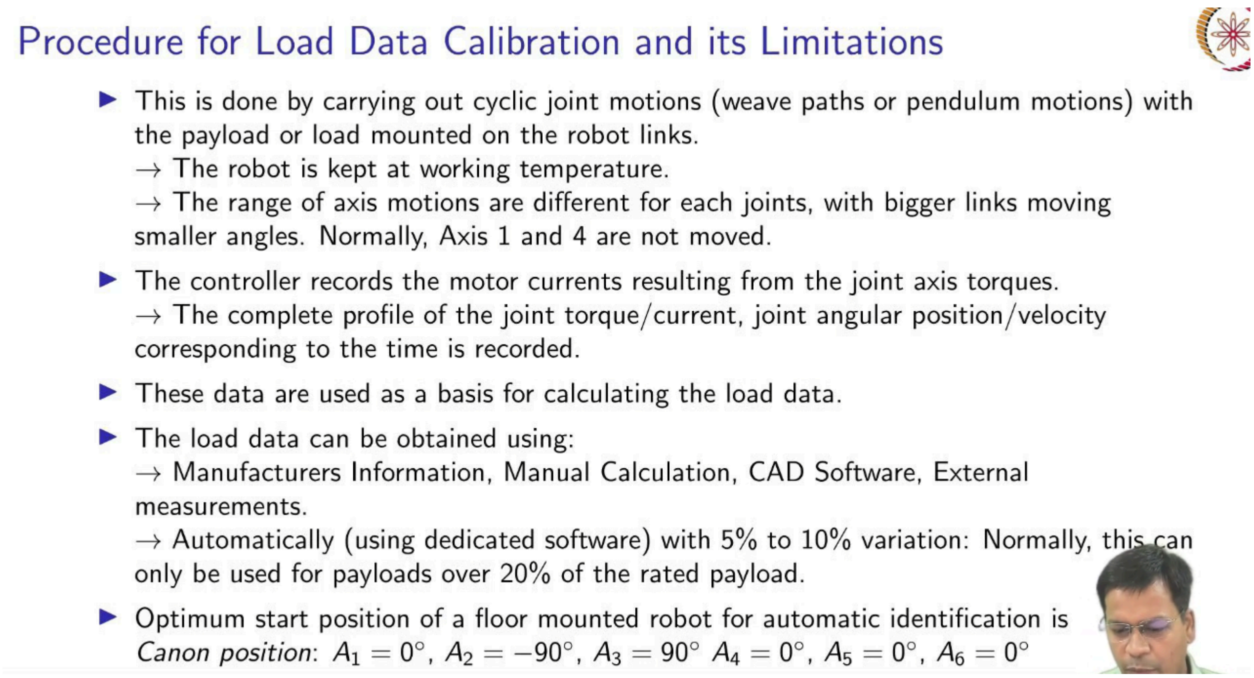
NOTE: The robot must not be operated with incorrect load data. Failure to obs
this may result in considerable damage to the robot (affects its service life), its
environment or any human injury.

So, let me just introduce you to Load Data Calibration, why that is important, how it is done, and so on and so forth. So, it makes the dynamic model of the robot more precise. You saw your dynamic equation of motion. It looked like this: I torque is equal to I theta double dot. Everything is vectored out here. Those are a few matrices. This is a matrix. Tau is equal to I theta double dot plus C theta, theta dot. It is the function of theta and theta dot. And then you have gravity compensation, torque. That is the only function of theta.

$$\boldsymbol{\tau} = I\ddot{\theta} + c(\boldsymbol{\Theta}, \dot{\theta}) + y(\boldsymbol{\Theta})$$

So, you see, the inertia term is there, and it is a significant term. It carries a huge amount of value, and it contributes a lot to the torque, which is going to come at the joint and same with the robot is moving at a good velocity. You will also see velocity affects the torque. So, this is the contribution due to the centripetal and Coriolis effect. That is, again a function of mass also. So, there are masses of links that go here. This is the velocity which comes here. If velocity is significant, this term becomes quite significant. So also, in case the robot is not moving, knowing the mass is also very important because this is the gravity component. When you see torque, the contribution of this element to the torque that holds the robot in its place, or it just moves at a slow velocity. So, these are the terms. You see, there are plenty of good amounts of contribution of the moment of inertia and masses to this torque. So, knowing these values more precisely will help you to communicate your controller about your robot itself, because the controller runs in a closed loop, so it also continuously tracks the errors which are there in the trajectory. So, quite a lot of time there is model-based control in which you use this particular model of your industrial robot to feed-forward your robot with that torque and then check the errors and use some gains to control the robot more precisely. So, that is what is used in most of the industrial robots. So, in this case, the dynamic model is more refined. If you put the values of the moment of inertia and the masses, your dynamic model becomes much more refined in that case. So, model-based trajectory control is for complex motion profiles. You had seen earlier in our application videos when I showed you a robot doing a glueing operation. It was moving in a free-form shape, and it was doing that glueing operation. There are painting operations also. Also, the trajectory is very, very complex, and in the case of laser cutting, you have seen. So, there are many applications in the industry in which your robot makes a complex motion and trajectories are there. It is not just the path which is important, and it is the trajectory also which is important. That means for each and every point, you have a fixed set of joint angles and the Cartesian values of its end effector. So, those points are not just freely stated in the space, they are to be there in a manner when time is also varying right. So, each and every point, the point where it is defined with respect to the time. So, that is.Why your acceleration profile is important, your velocity profile is important. So, everything becomes very, very critical in that case when the trajectory is there. So, model-based trajectory control, and that is for complex motion profiles, you need the moment of inertia and your masses which are there in different components. They are very, very important. So, the controller plans the optimal motions using the correct dynamic model, which calculates the time-optimized motions. So, it calculates the time-optimized motion that enables close acceleration adaptation. Also, if you have considered a motion, let's say you have taken a motion profile for your joint, so it will closely match with the accelerations which are there at different instances of time along this motion profile which is chosen. So, having your dynamic model correctly defined makes your controller more closely track this trajectory for the joint as well. As that results in a good trajectory following the end effector. Also, this prevents any mechanical overloading of the robot. Let's say you have no idea, and you just consider this one. Let's say you have I theta, double dot for the torque, which is coming here. Forget about the rest of the term. If this robot is moving at a huge velocity and acceleration. You see, this creates a torque, which is here, apart from what is going to come, due to the gravity component only. So, there is the torque which comes due to this motion. So, if this is not precisely known, let us say we know it, but not to the actual value, and the actual value is much higher when it is actually moving. In that case, that would cause more amount of torque that comes into the mechanical system, especially your links, your gear units, your bearings, and each and every thing which are there in your system. The whole of the mechanical system may get overloaded, right from the foundation to the joint which comes at the end. So, the whole of the system is at stress in that case. So, you can prevent that using precise knowledge of your system. Moment of.Inertia and your masses, which are there, right? So, that is to be done, and it also prevents any electrical overloading. If you are, your system is loaded with a huge amount of torque. unknown torque. Basically, known is the only thing which is going to come because of the mass and moment of inertia of the links. But you also have added supplementary loads. You also have additional attachments at the end. That is the tip of your robot, your end effector may be. So, those are also going to create some torque, so that additional torque I am talking about, not the link and joint torques only. that prevents electrical overloading. If you know that precisely, it will prevent any electrical overloading, which means you know all the motions, all the torques, and all the currents which are going to come. You know it well. So, while moving along the trajectory, the controller will calculate currents which are which should be flowing at that moment more precisely. So that you don't get overloaded. Your load data basically basically comprises two things. First is the static load, which is only because of the masses which are there and the location of the centre of gravity, got it. So, that is going to create a moment, a static moment. You have seen it in the case of statics, and the gravity compensation torque is going to come at the joints. that was calculated only due to the link masses. But there are masses which are overrun by the robot. like supplementary loads to different links. We will talk about that. So, those masses are also going to create some static moments. So, mass and centre of gravity, and location of those masses are to be known for static loads calculation also. You also have dynamic loads which are going to come. That is due to the mass moment of inertia of any added loads. This excludes the links because the model of the link, moment of inertia of the link, and masses of the link are already fed by the manufacturer to the controller. So, that is, this data is already there with the robot. You have to find out how much, is this got it?

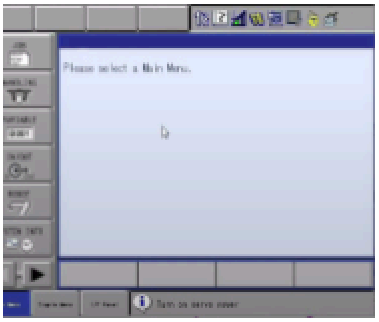
What if you don't do this? The robot must not be operated with incorrect data. Failure to observe this may result in considerable damage to the robot. You see, it affects the service life of your robot. If gears are loaded more than required, there will be more wear and tear. That is there in the gear boxes, in the bearings. It can also cause considerable damage to the environment which are around the objects which are lying around why. If the robot fails, it may hit the surroundings, too. If it fails considerably, in that case, it can also injure a human who is around who is working along with the robot. Maybe he is programming, and he is handling the robot and systems. So, that is what. So, it is a warning which is placed in any robot manual. So, this is a prerequisite. Before you put your robot to use, you have to do this task, that is, Load Data Calibration.



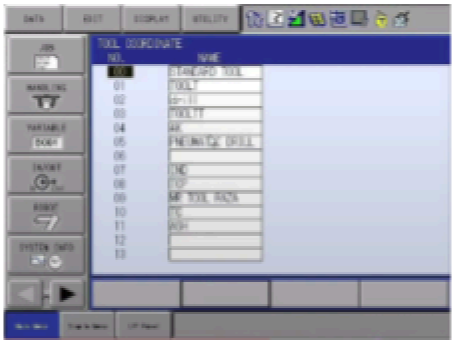
Procedure for Load Data Calibration and its Limitations

- This is done by carrying out cyclic joint motions (weave paths or pendulum motions) with the payload or load mounted on the robot links.
  → The robot is kept at working temperature.
  → The range of axis motions are different for each joints, with bigger links moving smaller angles. Normally, Axis 1 and 4 are not moved.
- The controller records the motor currents resulting from the joint axis torques.
  → The complete profile of the joint torque/current, joint angular position/velocity corresponding to the time is recorded.
- These data are used as a basis for calculating the load data.
- The load data can be obtained using:
  → Manufacturers Information, Manual Calculation, CAD Software, External measurements.
  → Automatically (using dedicated software) with 5% to 10% variation: Normally, this can only be used for payloads over 20% of the rated payload.
- Optimum start position of a floor mounted robot for automatic identification is *Canon position*: $A_1 = 0^\circ$, $A_2 = -90^\circ$, $A_3 = 90^\circ$ $A_4 = 0^\circ$, $A_5 = 0^\circ$, $A_6 = 0^\circ$

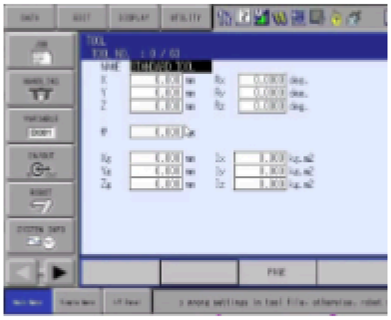
So, yes, there are procedures for load data calibration and there are some limitations also. We will discuss that. So, this process is done by carrying out cyclic joint motions, V path or the pendulum path motions are commonly known as V path or pendulum motion in different robot terminologies- with the payload. The payload is already there, and loads are mounted on the robot. Link that. Those are the supplementary loads. Along with all those loads, you have the robot controller, or you can cyclically move the robot and observe the torque noted down, and then you can calculate how much those payloads are or how much are those supplementary loads. Robots can do it with automated programs which are there, which are supplied along with the robot, or it comes as an add-in, plug in to the robot controller software. So, the robot is kept at the working temperature. While carrying out the load data calibration, the robot should be at its working temperature only. You know that also affects the torque because the viscosity, the damping, which is there at the joint that may change, and the density of the object changes. So, having that in the correct working temperature will let the robot know your dynamic model more precisely when it is actually working. So, you have to get very much closer to that. There are procedures which are there in the robot, which are known as warming up procedures. So, before you perform this test, you have to do a warming-up procedure. So, the range of axis motions is different for each joint. That is done if it is automatically done by the robot, with the bigger links moving at a smaller angle. That much should be enough because a bigger link, even if it moves by a smaller amount, gives a sufficient amount of data in order to calculate any supplementary loads. Normally, axes 1 and 4 are not moved. You see your axis 1. Axis 1 was the perpendicular to the ground motion. if your robot is like this, this was your axis 1, and then you have axis 2, which was here, we have axis 3, which was here, and you had axis 4, which was moving, your spherical centre, risk centre. About this axis, about this axis, you see, moving this doesn't cause much change in the current; moving about axis 4, even if you have a payload, hardly changes much of the torque, which is going to come at different joints. So, that is the reason this is not much moved, even axis 1 because it is moving. Normally, they move at a very slow speed, and even if they move, it is not moving against gravity, so the torque variation is not much because of this. So, these are the reasons why this is not used while identifying the load data. So, a few robots use this motion also in order to find out the moment of inertia, but definitely not due to, not while calculating the static load. So, yes, the controller records the currents that result from the joint axis torque while it is moving. the complete profile of the joint torque and the current joint angular position and velocity corresponding to the time is recorded. So, that means it wants to make this equation once again: c theta theta dot and gamma theta. So, it is going to use the whole of this equation and calculate using the Precise measured joint position and velocity. Feed it here, and it will check how much the error in torque that is going to come iteratively. Using that, it will calculate all the moments of inertia and the masses. these data are used as a basis for calculating the load torque and the load data. The load data can be obtained using the manufacturer's information. If you have attached any supplementary load, you have complete information about its centre of gravity, its moment of inertia and shape and size. You can put that directly to the robot controller through numerical inputs in its teach pendant or by manual calculation if you can do it. You can calculate, and you can put that. So, there are procedures, and you know how to calculate equivalent moments using the moments. Where does your actual centre of gravity location lie for the set of bodies? Or, same way, you can calculate for the set of bodies: where does your moment? How much is your moment of inertia resulting out of a combination of multiple known bodies? If you have CAD software or by doing some external measurement experiments to find out that. So, these are the ways how you can load the load data for your added masses and these can be done automatically using dedicated software if you have that provided by the manufacturers. With almost 5 to 10 per cent variation, it can be done very closely. But normally, this can only be used for payloads only, not for the supplementary loads and over 20 percent of the rated payloads. So, the supplementary load can be almost around 20 percent of the rated payloads. So, these are some limitations, what I have told you. So, when I am using an automatic method to identify my loads, there are errors to that. they are not very, very close values that you can obtain closer one if you know the system properly through this information. So, the optimum start position for a floor-mounted robot for automatic identification is the canon position. You already know that. I will show you a video now that will show this canon position more properly. So, for that access, 1, 2, 3, 4, 5, 6 for a 6-degree-of-freedom robot is like this: it is nothing, but it is something like this. you have, this is the ground frame, and the robot stays in at least this position.



Front Screen of teach pendant



Tool Coordinate

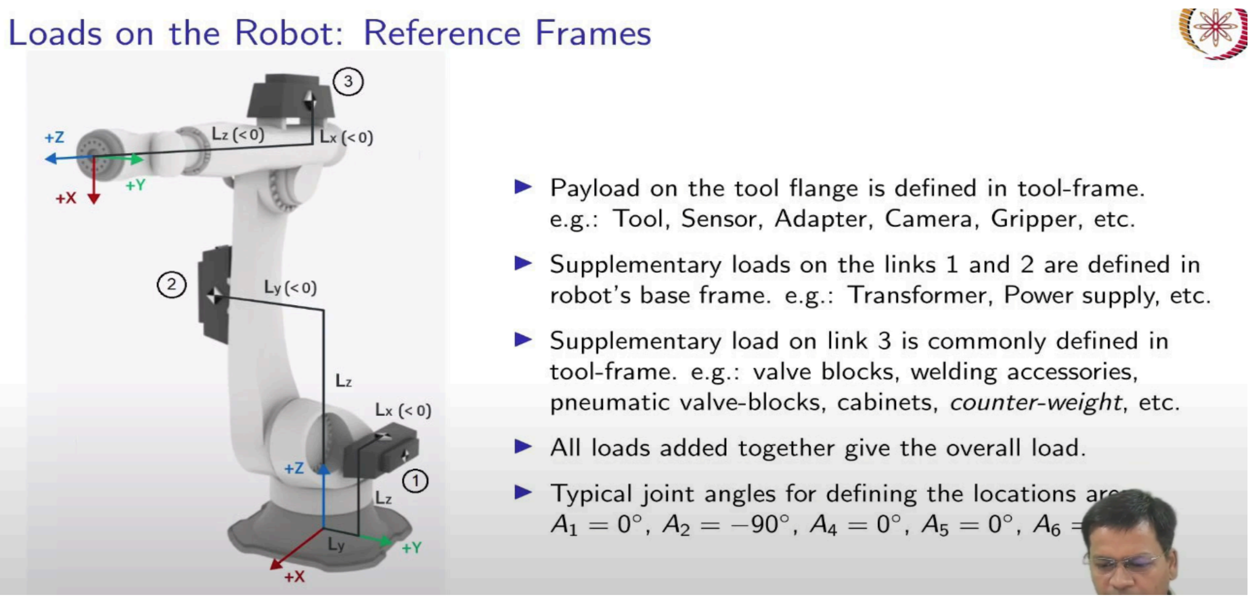


Blank Data

Load setting on U-Arm

So, let me just show you a small set of demonstration videos, in which there is an application which is mounted, which is put to the robot controller, and that allows me. This is for Yaskawa GP12 robot. So, you see, it is something like this in which you have to start like this: this is the front screen of to teach pendant I have captured, and in the next case, I have just used the tool coordinate system, which is to be taken. There are multiple tools which can be attached to the robot, and they can be taught. You have already seen this in the case of TCP calibration. So, you have the multiple number of tools that you can have. You have to select the proper tool here, once that is done, this is the blank data which is shown here. This is the blank data. You see, everything is 0, 0, 0. So, the values which are here. You see, this is: this is nothing but 0 0, 0 and 0 0 0. This comes from the TCP calibration, which is the offset of the tool centre point from the flange. So, this is the data which comes from there. This is the weight of that. This is to be identified, and the location of the tool is to be identified, and the location of the centre of gravity is to come here. This is the moment of inertia which is to be fed here. It can be done manually, but now, this robot will do it through its automatic code. You see, this is all-star, star, star. Now it is asking me to consider the added mass, if it is there in this because now I am going to perform tool calibration tool load calibration. So, it is also asking whether to consider any additional load if it is there on the U-Arm, it may be considered or it may not be considered. So, if I select to consider, it does some sort of motion for the home position. So, now let me show you the video.

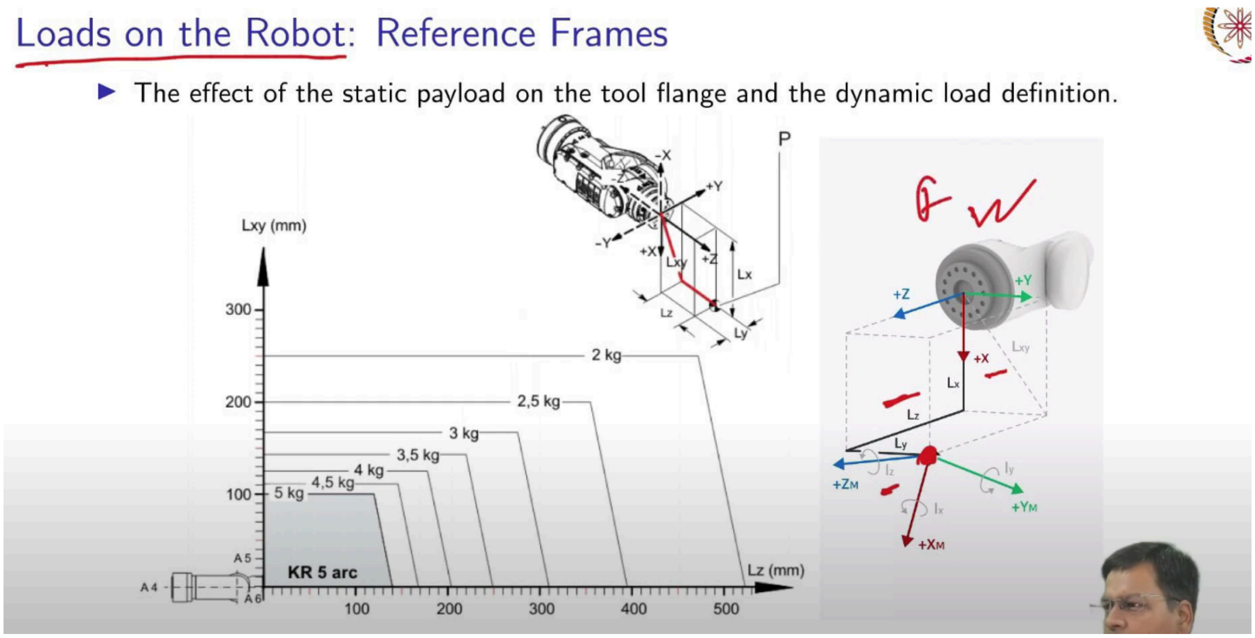
So, the robot is, it comes to the canon position first. Then it will do a sequence of motion and it will try to find out everything. So, Xg, Yg, and Zg are found out by the first motion. Let me just run the video now. So, this is the initial position where I started. It gradually went to the canon position. As soon as it came here, it made some small motions to find out. That is, the Xg, Yg, and Zg positions were found. So, two different angles are required. One is like this, and another one is like this, that is, it is probably trying to calculate the moment which is come due to gravity. So, how is it calculating the moments? It is based on the current data which is there in the motor of your robot. So, that motor, using that current data, you can calculate the torque. So, it is used because it has no implicit torque sensor at the joints. So, it basically calculates everything based on the current data and that is the reason why it is not very accurate. Now, it is trying to find out the moment of inertia as well with this motion. What you can see now, it will take it to the home position once again, and it will find out all the moments of inertia, ix, iy, and again, by making some other motion, it will try to find out the moment of inertia about z, also, and finally, it takes you to all the values you see, because this gripper is almost slender, and it doesn't have much of a mass distribution along z. So, it took it as 00 now, but it could precisely find out the centre of gravity location, which you can see here, and the moment of inertia about x and about y because it is a very extended link along x and y. It can calculate that, you see, and this data, what you see as 000, will come directly from the TCP calibration. So, normally, the TCP calibration as well as this load calibration, comes together in a single menu. So, this is how it is done automatically by the robot. If you know your system well, that means you have full knowledge of CAD through manufacturer data or through experiments that we have discussed. You can directly feed in here. That will be much more accurate as compared to this automatic calculation.



Loads on the Robot: Reference Frames

- Payload on the tool flange is defined in tool-frame. e.g.: Tool, Sensor, Adapter, Camera, Gripper, etc.
- Supplementary loads on the links 1 and 2 are defined in robot's base frame. e.g.: Transformer, Power supply, etc.
- Supplementary load on link 3 is commonly defined in tool-frame. e.g.: valve blocks, welding accessories, pneumatic valve-blocks, cabinets, *counter-weight*, etc.
- All loads added together give the overall load.
- Typical joint angles for defining the locations ar $A_1 = 0°$, $A_2 = -90°$, $A_4 = 0°$, $A_5 = 0°$, $A_6 =$

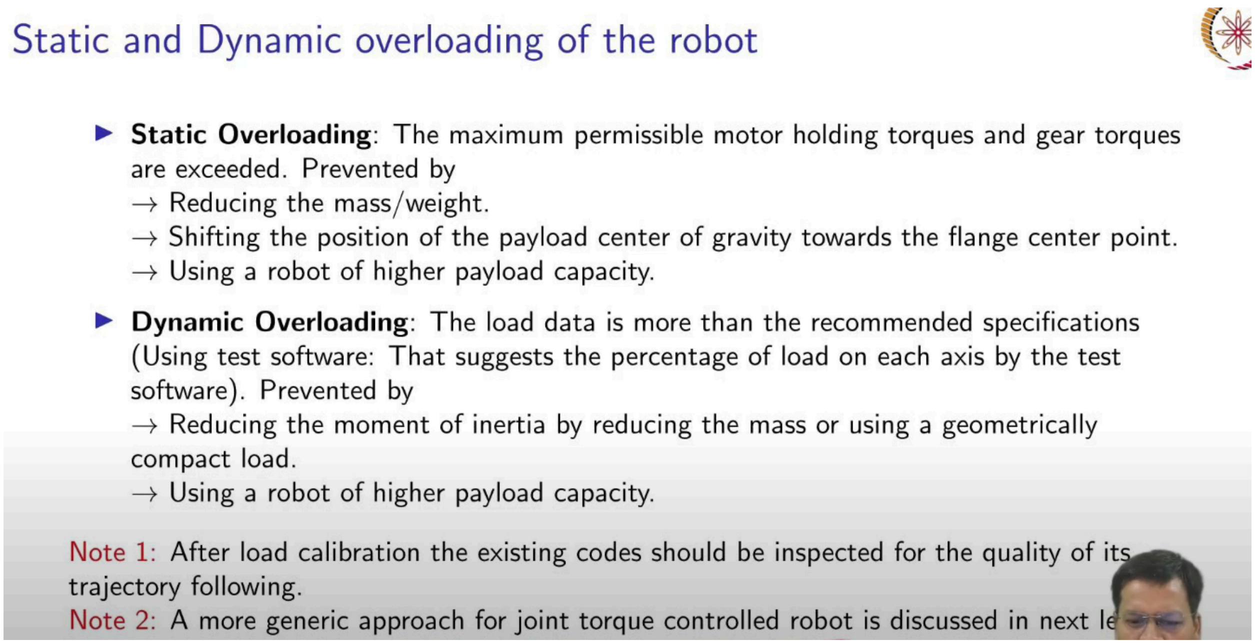
Now, where are the reference frames? How has it actually stated those mass locations? Those are the loads that come on to the robot links and the payload; the payload on the tool flange is defined in the tool frame. So, if there is a tool frame, the payload which comes after this tool frame anywhere over here can be calculated based on the frame which is attached here, so any displacement will be mentioned with respect to the frame which is attached over here, that is, the tool frame. So, in those cases, what could be your payload? The payload can be your tool. Anything that comes after your flange is your payload. So, the robot, when it is delivered, if it says it is a 12 kg payload robot, it is with nothing. It should not have any tool. It doesn't have any sensors, adapters or anything. So, this could be your payload. This all comes under your payload. Adapter camera, gripper, and the mass that you are actually carrying. If it is a gripper, it can pick up something. So, that also is a payload. Overall the payload is the sum of everything which is attached after this flange. So, that is the payload. We have already seen it when we were discussing the technical specifications of the robot. So, this is your payload, and it is defined with respect to the frame, which comes here at the tip. This is the flange robot flange which is there. It is commonly known as a tool flange. And then, you have a supplementary load on links 1 and 2. So, this is your link 1. and you have link 2 which is here, got it? So link 2, and these loads which come here are defined with respect to the base frame. That means when it is defined, it is defined with respect to this, although this link is moving. That means you have to bring your robot to this cannon frame. This is the cannon position of the robot. So, in this cannon position, only this is defined. So, the common load that comes to these 2 links are transformer. It can be a power supply. Any heavier load should come on these 2 links. It should not come somewhere over here, got it? That is on the link 3. Link 3 should have only the smaller load, and there are many a time it can be a compensating load. Sometimes you have a huge payload which is there. You can have a compensating load also here which has not much of a function other than compensating the load which comes here. So, that is a supplementary load that comes on links 1 and 2. Link 3 is commonly defined in the tool frame. So, because it moves along with this, this link. That includes axes 4, 5 and 6. So, link 3, whatever comes on link 3, is defined with respect to the frame that comes here. That is the tool frame. The common inclusions for that load are valve blocks, welding accessories, pneumatic valve blocks, cabinets, and counterweights can also be there. As I told you just now, all loads added together give the overall load that is going to come on the robot. So, the whole of the load should be summed together. Typical joint angles for defining this location. This is the cannon position which is defined here. Is this one? Got it.



Loads on the Robot: Reference Frames

- The effect of the static payload on the tool flange and the dynamic load definition.

Now, the effect of load on the robot. So, if it is only the payload, this is given even in your datasheet. So, where can it lie? How it should be. So, you see, it is defined with respect to the this is the centre of gravity location of the payload, which is there. It is defined with respect to the tool flange, which is there with respect to the tool flange. So, this is the x offset, z offset and y offset, so all three together will take it to this location. So, this location is defined precisely with respect to the tool flange, which is here, and the influence what it can do is: you see if you are within this region, so this is Lz, how far away it is along this direction. This is your z-axis. So, that comes here. So, whatever this is, if you take it more along this if it is a 5 kg payload capacity robot, I have taken it from the KUKA KR 5 Arc robot data sheet. So, till here, it can manage with a 5 kg payload. If you take it further away, after this much distance along z, your payload gets reduced. You can carry less load. In this case, it is 4., 5 kg, and then you can carry 4 kg, 3.5 kg, 3 kg, 2.5 and 2 kg. You see, the further you go, the same the weight, and the same load is going to create more amount of torque. If you go further, torque gets increased, which actually comes to the joint which is there. So, that is the reason you are limited by, because you are limited by the torque which this joint can handle. So, you are limited by the moment you are going to handle and in the same way, and the weight gets reduced if it goes further away. Right, and it is there also along XY. So, this is the XY distance, which is here, and that is mentioned here. So, if you increase along XY again, you see you have less amount of load that you can carry. This is the static load calculation only. This is what is given in your datasheet. But the dynamic load will be even less OK. So, that also depends on the shape of your object, not just the centre of gravity location. Also depends on the shape of your object. So, that cannot be so easily defined, so in order to do so that robot has to make some motion also because those are the dynamic torques. You have to find out the moment of inertia. Got it?



Static and Dynamic overloading of the robot

- **Static Overloading**: The maximum permissible motor holding torques and gear torques are exceeded. Prevented by
  → Reducing the mass/weight.
  → Shifting the position of the payload center of gravity towards the flange center point.
  → Using a robot of higher payload capacity.
- **Dynamic Overloading**: The load data is more than the recommended specifications (Using test software: That suggests the percentage of load on each axis by the test software). Prevented by
  → Reducing the moment of inertia by reducing the mass or using a geometrically compact load.
  → Using a robot of higher payload capacity.

Note 1: After load calibration the existing codes should be inspected for the quality of its trajectory following.
Note 2: A more generic approach for joint torque controlled robot is discussed in next le

So, static overloading and dynamic overloading are what it is. So, static overloading is the maximum permissible motor holding torques and the gear torques. If that gets exceeded, it is known as static overloading. So, this can be prevented by reducing the mass and, thereby, the weight of the load. That is going to come shifting the position of the payload centre of gravity towards the flange centre point. You have seen it just now through the table which I have shown you. So, you have to reduce that offset distance from the flange, which is there, or you can use the higher capacity robot that is not always in our hands. Once you have selected a robot, you have to prevent any overload that is going to come to that.

Again, dynamic overloading: the load data is more than the recommended specification and that can only be found by doing some tests. Tests are done using the test software that suggests the percentage of load on each axis by the test that the software performs. In the case of industrial robots, you cannot check the torques very precisely. You cannot even know the current which is going to flow by moving a load right. It doesn't give you much access to those parameters. In that case, you have to depend on the software only, which is provided along with the robot and, more so, the mathematics that goes behind it. That includes quite a complex electromechanical model. That doesn't mean it goes beyond the scope of any user, but that can be done only with the available data which you have. So, you have to depend on the test software. But in the case of a research robot that can run on torque control and that allows you to check the torque at the joint and current precisely while it is running, then you can do further experiments. We will discuss that later in the next lecture only. So, that is what we are going to do in the next lecture.

So, this can be prevented by reducing the moment of inertia. How can that be done? By reducing the mass distribution, reducing the mass or using a geometrically compact load. This effectively reduces the distribution of mass. It is making all the masses which is distributed in the volume come very closer to the axis of rotation. So, this is what is to be done, and using the robot of higher payload capacity. Again, this is not in our control all the time. Please note after load calibration, also any existing codes if you have already done some programming of your robot to perform, let's say, a welding task; if you have done this load calibration, you have to redo that programming, or you have to check the accuracy of the motion if it is doing. If you have made it go with a 2 mm gap throughout the trajectory from the surface so that the 2 mm gap may not retain as it is after the load calibration, you have to redo that and check the quality of the trajectory following. So, this is to be noted again. A more generic approach that uses a torque-controlled robot will be discussed in my next lecture, which I will be doing. That uses a standard industrial robot, but I have an axis to its motor current, so using that, I will discuss how to find out the load data as well and how to compensate for that. So, that is what I will be doing in my next lecture. So, for this lecture we are done. That's all. Thanks a lot.