NPTEL Online Certification Courses
Industrial Robotics: Theories for Implementation

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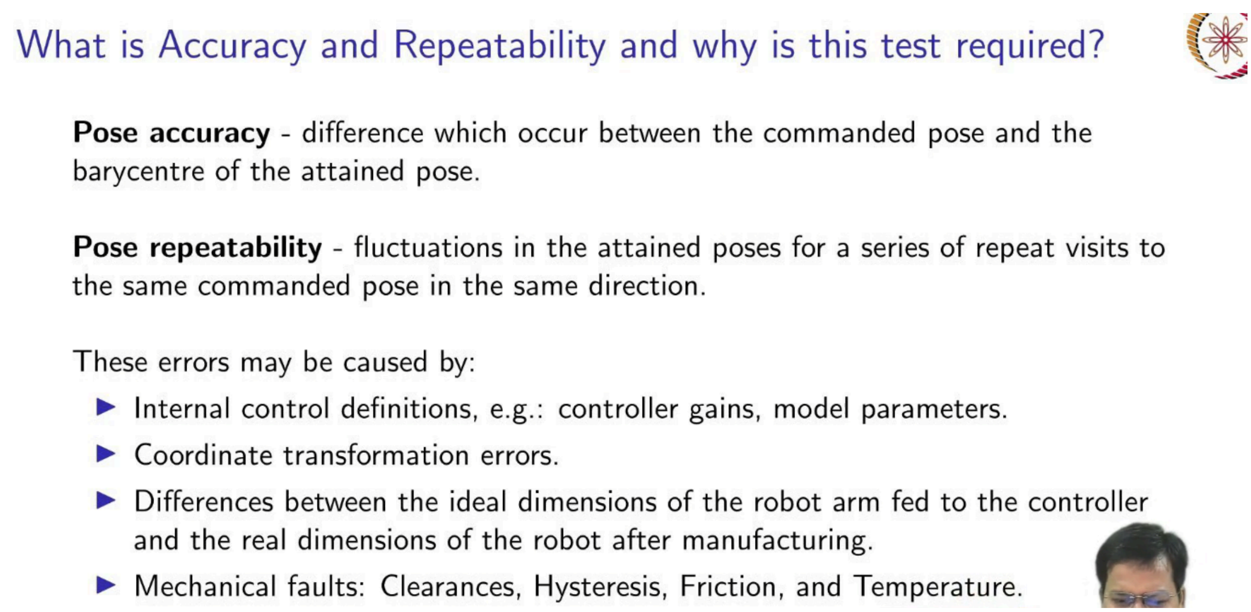
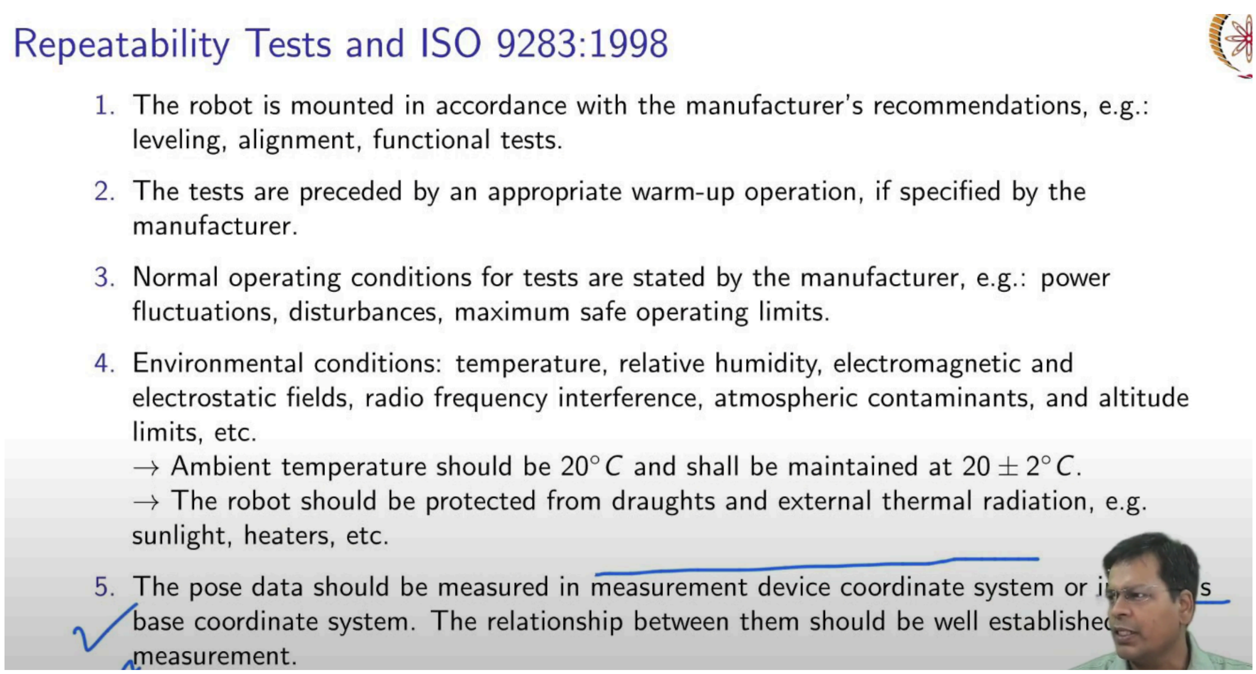
Week: 10
Lecture 42

Repeatability Tests and ISO 9283:1998

Welcome back. So, now that you are already introduced to various technical specifications of an industrial robot that determine the performance and capabilities of any industrial robot. So, now, in today's lecture, I would stress upon repeatability test. This is one of the most desirable tests that is applicable or relevant to any industrial application. Other important tests are velocity characteristics, drift path, repeatability or path accuracy, cornering, deviation, etc. So, now, without much delay. So, let us start with today's lecture, where I will be focusing more on repeatability tests. That is something that you have also seen in the datasheet that I have shown in my earlier modules. So, let us begin.

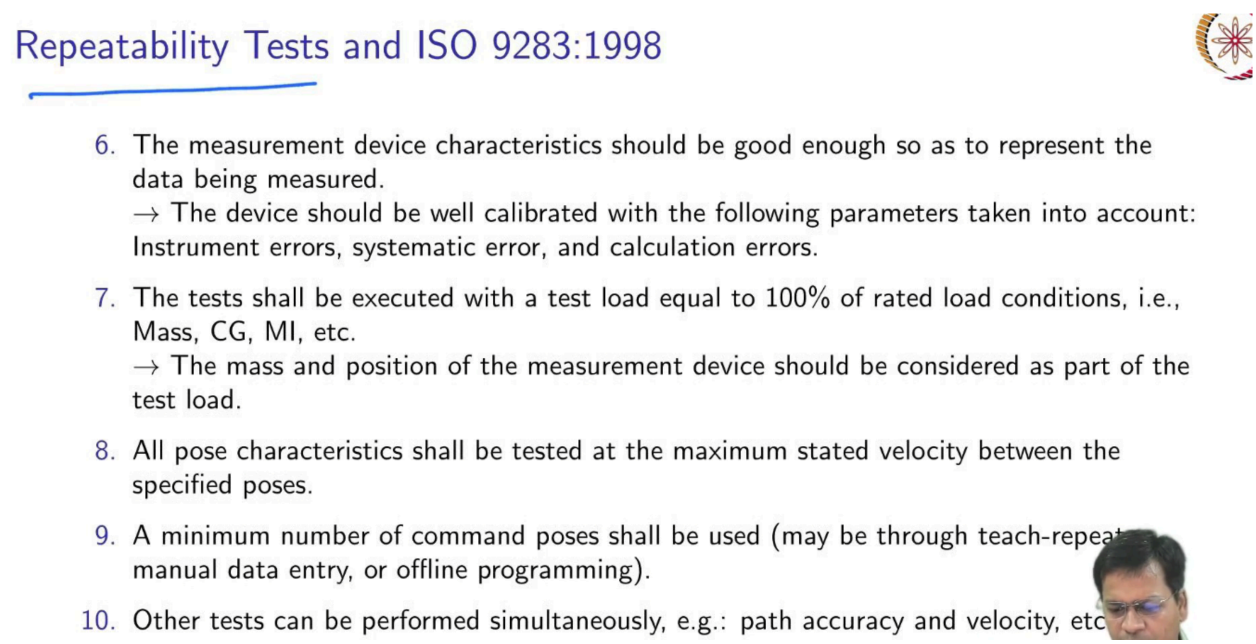


So yes, before we actually get into the repeatability test, one more parameter which is very close to repeatability is accuracy, and that also is very much desirable, and that is quite a lot of time is also mentioned in the datasheet of some of the robots. So, let me also introduce this along with repeatability here. So, pose accuracy: pose are basically position and orientation. So, pose accuracy is the difference that occurs between the commanded pose and the barycentre of the attained poses. So, you see, you have commanded the robot to go to a certain place, and then your robot goes to a different place somewhere. So, it is the difference between the commanded pose, that is, this one, and the barycentre means the, almost the centroid, the most of the point where it lies. So, between that and this, whatever the distance is known as the pose accuracy, and similar in the case of position, it is easily visible geometrically, but in the case of orientation, it can be very much analogous to this, in which you have a commanded orientation and the attained orientation in terms of angles along the axis. So, this is what is accuracy, pose accuracy and what is posed repeatability. It is basically the fluctuations in the attained poses for a series of repeated visits, a series of repeated visits to the same commanded pose in the same direction. So, we will discuss more upon this further in this lecture. So, I will discuss this very thoroughly now. So, these are the errors, and they are mostly caused due to internal control definitions. Examples: controller gains, model parameters. If the model is not proper, which is there with the controller, or after the assembly, the model has little deviated. This error may be there. If you command the robot to go to a certain place and it goes to a different place. There may be some deviation between them, So that is the model parameters. What were the model parameters? If you can recall, that is the moment of inertia, mass, so the centre of location of the mass. So, these are some of the models which are there with the controller already. So, that defines the dynamic equation of motion of your robot. So, that is the model parameter I mean here, and the controller gains, that is. You have seen it in the controller module also. What are controller gains, basically proportional, integral or derivative gains. So, if those parameters are not tuned properly, in that case also this deviation can occur. So, others are kinematic transformation errors or coordinate transformation errors. If you have not calibrated your system well, this error can also happen. You need to know the precise dimensions of your link. Link offset and link joint offsets should be known. So, those are the DH parameters if they are not precisely calibrated, this error can also occur. The difference between the ideal dimensions with the robot arm fed to the controller-that is the DH parameter, which is fed to the controller, and the real dimensions of the robot after manufacturing. There are some differences between them due to the manufacturing error or assembly error. So, it is mostly caused due to this and due to the mechanical faults. Basically, clearances if they are there, hysteresis, some friction, some temperature deviation if the links are very long, and you see some expansion in the link due to the change in temperature. So. this can also cause this type of error, that is, pose accuracy or repeatability errors.



So, the repeatability test is precisely defined in the standard called ISO 9283:1998, and it is still getting revised and updated every few years. And now this one is the one which is actually being followed. Before we actually do such a test, there are various guidelines before actually getting this test done. So, the robot should be mounted in accordance with the manufacturer's recommendation. Basically, the levelling, alignment, and functional tests are to be done. If it is to be mounted on the flat floor, or it is to be mounted on the vertical wall, or the ceiling may be on the inclined plane. So, if that is done, it should be precisely defined by the manufacturer, and the test people should actually follow that particular recommendation, which is given in the manufacturer's technical specification sheets or on the test sheets. What is recommended by the manufacturer? So, next is, the test should be preceded by an appropriate warm-up operation. Why is this important? You know, the joints or the links. They take some time to actually catch up with the actual dimensions due to the temperature changes, or when it is actually working, the temperature may be different in the environment where it is working. So, there are certain guidelines on the temperature also, and the robot, when it starts, takes some time to stabilise on its temperature. So, that is why the robot is made to run for a few minutes, a few hours before the test should start. It is specified by the manufacturer only. So, normally, the tests are done by a third party, not by the user or by the manufacturer. So, they follow some specific guidelines. So, there are guidelines given by the testing organisation and by the manufacturer. So, it depends on what is more important and how it should be done. It depends on the guidelines given by both of them. So, the normal operating conditions for tests are stated by the manufacturer. That is the power fluctuations. How much power fluctuations can it tolerate? So, that is, given. Disturbances in the load: how much additional load if there are multiple things which are clubbed to the same line, same power line? How much disturbance can it take? How much load disturbance can it take? Maximum safe operating limits are all defined by the manufacturer. So, a test organisation should always follow the guidelines given by the manufacturers since the other environmental conditions are also stated, like temperature, relative humidity, electromagnetic and electrostatic fields, radio frequency interference, atmospheric contaminants and altitude limits. So, all these are mentioned. And ambient temperature: the test organisation defines this. This is a standard condition for the test. This cannot be defined by the manufacturer. So, they do all the tests at this temperature, that is, 20 degrees centigrade, and it shall be maintained at 20 plus minus 2 degrees. So, this is the deviation. Deviation should not be more than plus or minus 2 degrees.

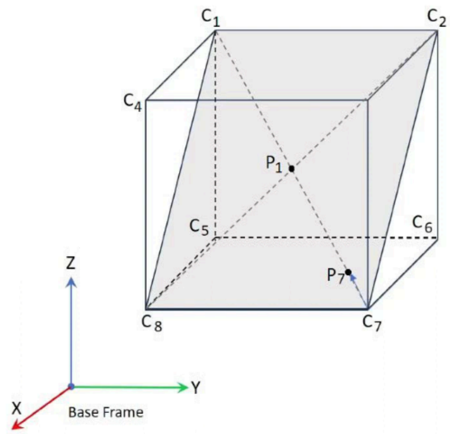
The robot should be protected from drafts. Drafts mean if there may be in the industry, there are forced air drafts, so that air should not directly fall upon the robot. So, it should be protected from drafts. External thermal radiations like sunlight any heaters if there are around. So, it should be protected from all of them. The post data should be measured in the measurement device coordinate system, so that is, with respect to the device coordinate system, you can measure the pose, that is, the position and orientation of your robot, or with respect to the robot base coordinate system. The relationship between them should be well established by the measurement also. So, only two coordinate systems are important here. One of them is the base of the robot, about which the robot's end effector is normally found using forward kinematics or anything or by the external measuring device, and the second one is the robot's measuring device coordinate system. So, with that, only you can measure the end effector, position and orientation.



The measurement device characteristics should be good enough to represent the data being measured. So, if you have to measure something in millimetres. So, your measuring device should be capable of measuring much below that millimetre, maybe sub-millimetre distance it should be capable of measuring. So, there are specific guidelines on that also. I won't go much deeper into it, but you should understand why it is so. So, if you have to measure a millimetre, your scale should not put its graduation in terms of centimetres. That is straightforward and simple. So, the device should be well calibrated with the following parameters taken into account that is, instrument error, systematic error and calculation error. All these three types of errors should be well calibrated, and those parameters should be taken into account while using the device. The test shall be executed with a load that is equal to 100% of the rated load condition. If the manufacturer says this robot can take a payload of 250 kilograms. The test should be carried out with 250 kilograms mounted at the end effector and the same with the mass, centre of gravity, location, the moment of inertia, etc. So, everything should be as stated by the manufacturer. So, the test, if you are making it move in a trajectory, the robot should carry that much load all the time, 100% of the load, while it is moving in the trajectory, even if it is stopping. So, all the tests like stopping distance, should also be calibrated using that hundred percent of the rated load conditions. So, it should be measured with that kind of load in place. So, the mass and position of the measurement device should be considered as part of the test load if the test device is mounted on top of the robot and effector so that, the mass should also be accounted for. If it is a 12 kg payload robot and you have another 1 kg. that is the measuring device weight. So, it should not go beyond 12 kg. So, the total mass should be accounted for. All the pose characteristics shall be tested with maximum stated velocity. If the robot can move at 2 meters per second, if the robot data sheet says so, the repeatability test should be carried out with the maximum stated velocity. The robot should start with 0, pick up the maximum speed and again go back to 0 at the maximum velocity, which is stated by the manufacturer or your what the controller can achieve between two endpoints. A minimum number of commanded poses shall be used. You should not command more than a single command in order to go to a single place. It may be through a teach pendant, that is, through teach and repeat thing, it can be done. You teach it to go to a place, and the robot repeats it to go to the same place. It can be in a teach-repeat format, or it can be commanded manually using manual data entry, or you can just define a set of points where a robot showed go, while this test is to be carried out using some offline programming technique also. So, all these can be considered commanded poses. Other tests can be performed simultaneously, like, if at all, you are doing a repeatability test, which takes a robot to a predefined pose. We'll discuss upon the predefined poses now only in this lecture only. So, coming back to this, other tests can also be performed simultaneously, which supports the same type of possessed in order to do that, like path accuracy or velocity tests that are also done with the same set, the same set of points, a similar set of points. So, those tests can also be done.

Definition of positions and repeatability tests

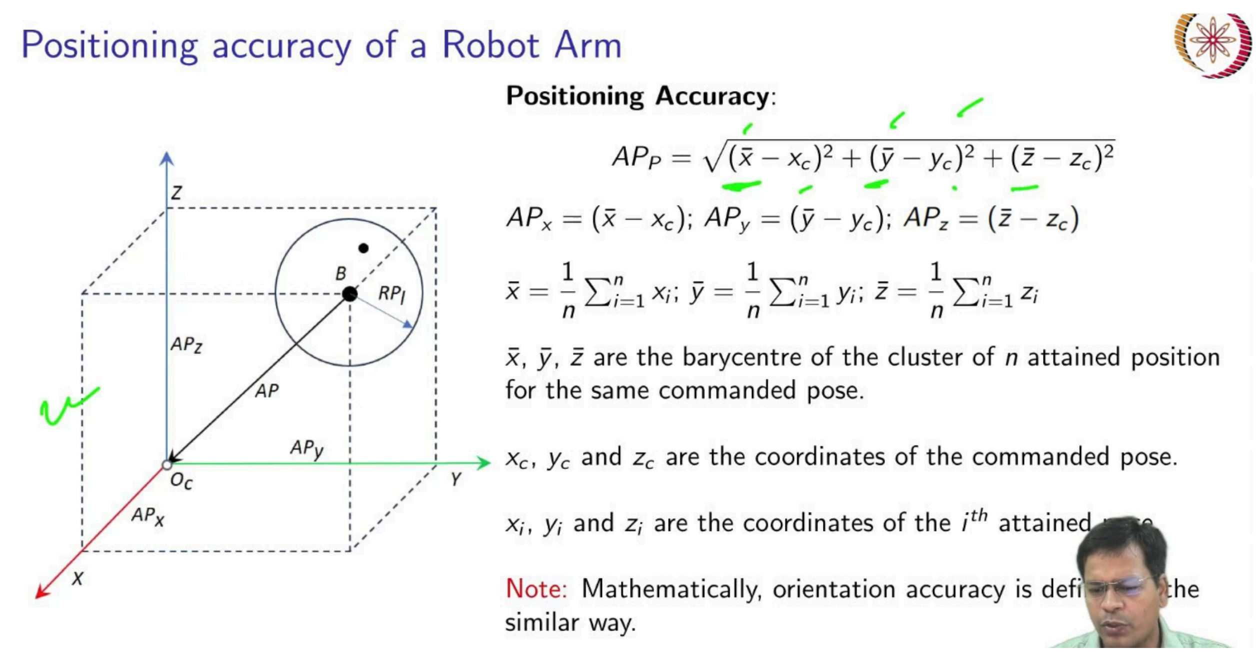
The cube or a rectangular parallelepiped.



NOTE: All the test conditions are to be specified in the test report.

- The *TCP* is moved to the designated corners of one of the cube-planes (Plane 1 for 6-DoF robot) in order: $C_1 - C_2 - C_7 - C_8$, $C_2 - C_3 - C_8 - C_5$, $C_3 - C_4 - C_5 - C_6$, and $C_4 - C_1 - C_6 - C_7$ for 30 number of cycles.
- The starting point P_1 is the intersection of the diagonals.
- The test path should be linear or circular. All joints shall be moved while *TCP* moves between the poses.
- The points are located at a distance from the ends of the diagonals equal to $10 \pm 2\%$ of the length of the diagonal.
- The cube shall be located in the workspace with the greatest anticipated use.
- The edges of the cube should be aligned to the robot's base frame with maximum allowable volume.

So, this is what is defined: where a robot should be taken when this type of test is done, like a repeatability test. So, these are the definitions of different positions. So, it basically defines a cube or a rectangular parallelepiped, and the TCP is moved to the designated corners of one of the cube planes. In the case of six degrees of freedom, you can only use one of the planes, which is marked over here in grey colour. There can be other diagonal planes or other planes of the robot, as well as of the tube as well, like, you can have a diagonal like given by connecting these two-this, this and this. There can be one diagonal plane that goes like this, or it can be yet another diagonal plane like this one. This can also be one of the planes. So, all the other planes are not very important if it is six degrees of freedom robot. So, in the case of the 6-DoF robot, only the one which is shown here in grey colour is considered. So, other planes are C1, C2, C7, C8, C1, C2, C7, C8. So, this is the one which is of our interest because we are mostly dealing with the 6-DoF robots, not like a SCARA robot. Another plane could be C2, C3, C8, C5. That is, C2, C3, C8 and C5, this, this, this, this, got it. So, you understand there are four different planes that can be used, and you have to go. You have to make almost 30 repeated cycles. You have to take the TCP to each of the points 30 number of times in order. So, it can be taken in order. So, there is one more point which is very much of interest. That is the point of intersection of the diagonals. That is the centroid of this cube. So, this is the first point. From where the robot actually starts moving, it goes to P1, then C1, C2, C7, and C8, and it has to do that for 30 number of cycles. So, the starting point is P1, that is, the intersection of the diagonals. The test part should be linear. It should go from one point to another in linear or circularly only. So, normally, linear is preferred, and all the joints shall be moved. So, while moving between any two points, all the joints of the robot should move. It should not happen that one of the joints remains stationary while others are moving while taking a bit of moving between two points. The points are located at a distance from the ends of the diagonals, which is equal to 10 plus or minus 2 percent of the length of the diagonal. If you see you have a total length of the diagonal is something like this. So, your actual point where the robot is taken is something like this: so you can go from here to here, so that is what is marked over here, C7, that is 10 percent of the diagonal. So, that is here: 10 percent plus or minus 2 percent. So, this is what is your 10 percent of, if this is your total length, and so it is 10 percent of total length, so that can be from here. So, the effective points are this. So, this is where your robot will actually go, got it? So this is where your robot will actually go, so, out of this total space which is marked by this cube. So, the 10 percent deduction is there along the diagonals where you actually take your robot while doing this test. So, the effective points are P1, P2, P3, P4, and P5, which are marked here by me no way, so the tube shall be located in the workspace with the greatest anticipated use. So, this tube should be located in the workspace of the robot, where you see your robot is actually to be used, and you should cover the maximum workspace so as to test your robot properly, and the edges of the cube should be aligned to the robot's base coordinate system and the maximum allowable volume. Let me just remove myself so that you can see it. So, the cube should be located in the workspace with the greatest anticipated use, and the edges of the cube should be aligned to the robot's base frame. So, you see, the robot's base frame is marked here, so the robot's base frame should be like this and your robot may be mounted something like this, and this cube should be in this workspace. Got it?

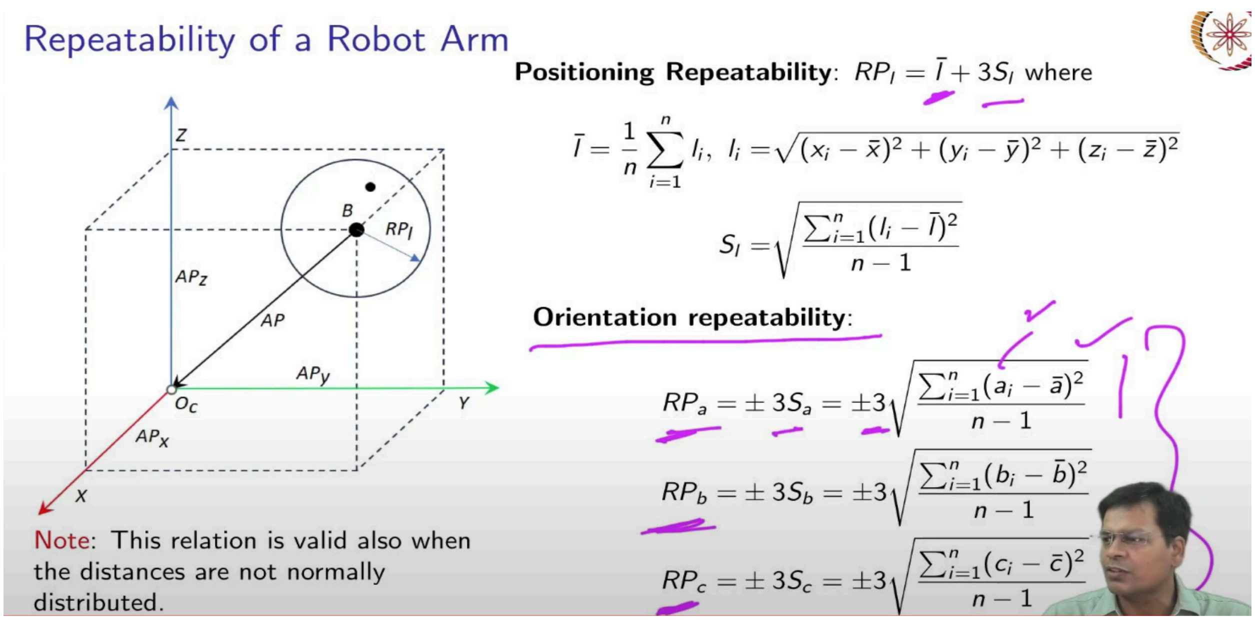


So, the position accuracy of the robot is defined. As there are different parameters, let me just talk about them one by one first. So, this is the actual point where it is commanded to go put it. So, this is given by O_C and your robot actually goes to a point which is here, and there are different points where the robot goes. So, every time you command your robot to go to this place, which is marked here as red, let us say. So, it goes to the location which is here, so these are the points, so you just take the mean distance of this. So, that is given by x bar. Similarly, along y, it is y bar. Along z, it is z bar. So, you take the distance which is known as AP_P, so that is given by AP, this is the one. So, that is, x bar minus xc. xc, yc, zc are the commanded location along x, y, z, and x bar, y bar, z bar is basically the that defines the barycentre of this, that is, the barycentre is b over here, so barycentre of this. So, you see, APx is nothing but this one.

$$AP_P = \sqrt{(\bar{x} - x_c)^2 + (\bar{y} - y_c)^2 + (\bar{z} - z_c)^2}$$

APy is this one. APz is this one. So, the x bar is basically the mean of all x if it is n number of times it is attempted to go there. Normally, it is 30, or more than 30 can be definitely done. So, it is 30. So, you take the mean of that. So, that is the x bar.

Similarly along y, similarly along z. So, commanded minus mean, commanded minus mean, commanded minus mean. So, those are this, so that is over here. You just take the square and take the root. So, it takes you to AP. So, this is this one. So, the x bar, y bar, and z bar are the barycentre of the cluster of n attained position for the same commanded pose. Over here, only the position is shown: xc, yc, and zc are the coordinates of the commanded pose. That is this one. So, basically, this is your position accuracy. xi, yi, and zi are the coordinates of the ith attained pose. That is basically used here in order to take the mean. That is the centre of the whole of the cluster, that is, the barycentre. So, this defines your positioning accuracy. So, mathematically, orientation accuracy is also defined in a similar way. However, it cannot be shown geometrically in a way like this. So, you can have in orientation if you command it to go to a particular orientation, so it just deviates from a little from that. Take the mean of all of them, 30 attempts altogether. That goes here, and commanded angles can go here. So, that actually goes here, and then you take positioning. That is the orientation accuracy. That can be done mathematically in a similar way. So, with this, we'll stop for the positioning here.



Let us go to repeatability here again. So basically, repeatability is defined by RPl is equal to l bar plus three times Sl.

$$RPl = \bar{l} + 3S_l$$

So, what are they? I'll define it here. So, what is l bar? l bar is nothing but one by n mean of all li, and what is li? li are now xi, yi, zi are the in any particular ith attempt, robot goes to xi, yi, zi location. x bar, y bar, and Zr basically define this point. That is the barycentre point. So, distance from the barycentre. For any ith attempt is taken here along x, along y and along z. So, this gives you the mean of all the squares, the sum of squares. So, that gives you li, so that goes here. l bar is like this, that is defined like this. So, li is defined like this. So, for each and every attempt you calculate li, take the mean of them. So, that comes here. So, sl is basically you take the sum of all i is equal to one to n li minus l bar square divided by n minus one square, the root of that, so it is similar to the root-mean-square of the distance. So, that is s_l.

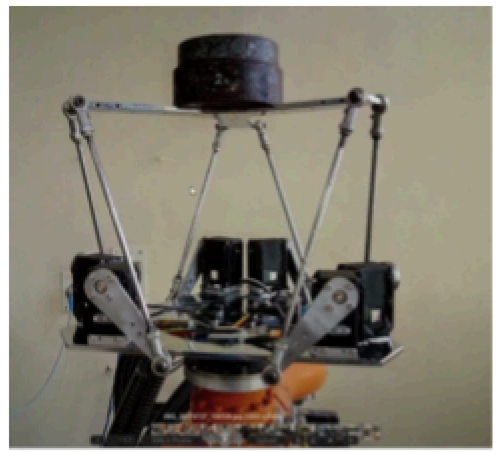
$$\bar{l} = \frac{1}{n} \sum_{i=1}^{n} l_i$$

$$l_i = \sqrt{(x_i - \bar{x}) + (y_i - \bar{y})^2 + (z_i - \bar{z})^2}$$

So, that goes here. And the l bar is calculated here only. So, this is your l bar, that goes here. Sl is defined here, so that goes here. So, total position repeatability is defined like this, not it.

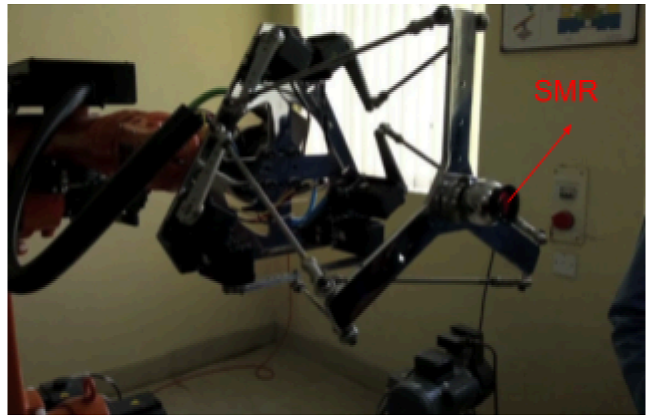
$$S_l = \sqrt{\frac{\sum_{i=1}^{n} (l_i - \bar{l})^2}{n-1}}$$

Similarly, the orientation repeatability: you don't have the term which is like this, so that is calculated along each different axis-is also of the coordinate frame, so that is along x, along y, along z in robot terminology it is also mentioned as a, b and c axes. So, it is nothing but three times of Sa. and again Sa is defined as ai. that is the with attempt, that is the angle attained along x. a bar is the mean of all the angles it has taken while attempting in multiple number of times. So, root-mean-square is taken like this: so that is three times of. That is basically your repeatability along a repeatability along b and repeatability along the c axis. So, that is defined. So, these definitions are precisely given in the ISO standard, that is, ISO 9283:1998. The relation is also valid when the distances are not normally distributed. It need not be normally distributed. It can be totally oriented along the same direction. So, even then, it is valid. So, it need not be normally distributed. So, this is what basically defines the repeatability.



So, let me just show you one case when we had a parallel robot, and we did it for that. So, let me just take you a visual walk through how that was done, so this is the robot, so this is a serial robot. Basically, I am not going to measure the repeatability of this serial robot, which is actually the chukka robot which is shown here, I will just move a bit now. So, yes, this is a parallel structure, which is shown here. This is a parallel robot, where you have, you see, you have an actuator here, actuator, actuator, and there are a total of six actuators that move the top platform. I will show you moving this platform, also how it is moved. So, effectively, I have fitted this robot at the end effector of the serial robot just to mount it, and there is no specific reason, and you see, you also have a load cell, which is here, that can basically take up the load, and you can precisely tell you how much load is carried by this end effector that is the platform of this robot, which is mounted here. You see, you have a controller over there that basically moves this platform, so, overall, this is the arrangement that I have shown here, closely. You can see it like this. So, these are the different links that actually move this top platform which is hereay, different angles I have shown here, so this is all. Now, it is arranged and fitted to the wall. It is similar to fitting the robot to the wall, and the robot is mounted like this. I want to check repeatability when it is mounted in this way, you see. So, this is your top platform, so that is what is going to move, that will remain stationary. So, what actually it is done? First, I will do some preliminary motion tests with the full load for which it is made, so this is the load test arrangement; when I am testing with 3 kg of payload, which is here, all the motions will be tested. So, now you can see almost all the actuators.

FARO laser tracker



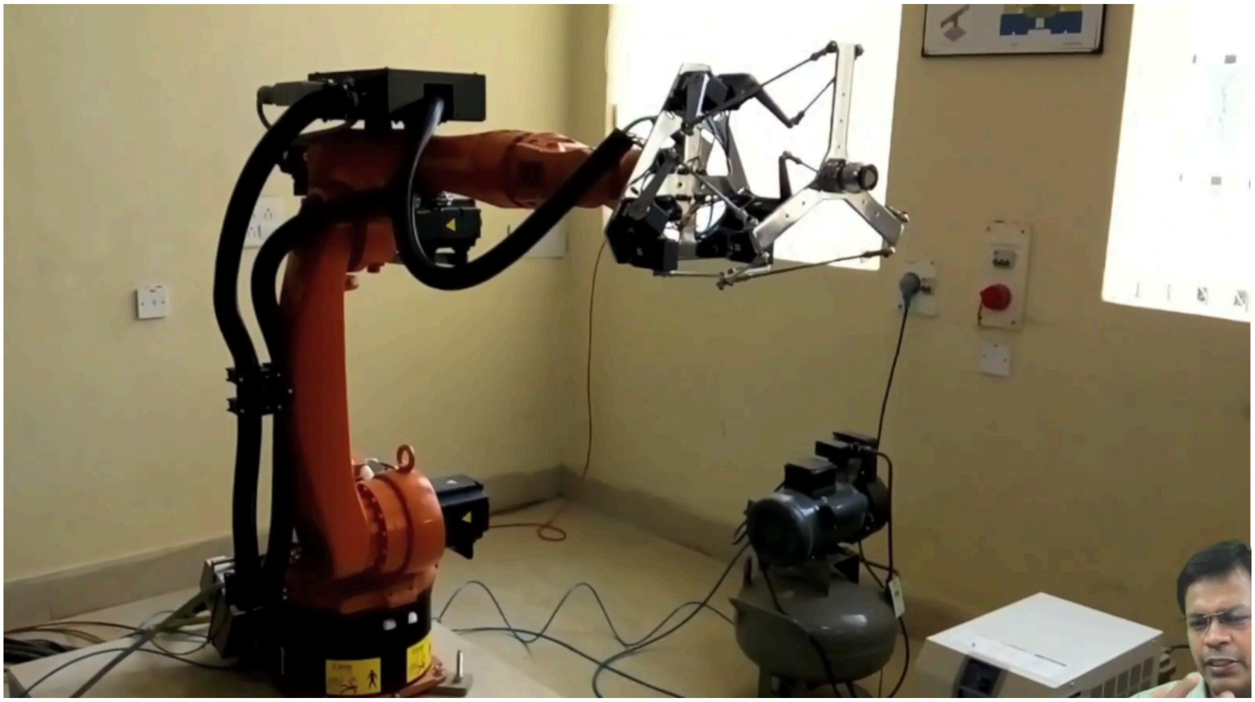
FARO laser tracker mounted on serial robot

FARO laser tracker close view

So, now this is a FARO tracker, a FARO laser tracker, so that can remotely sense any point which is fitted at the top of this robot which is here from a distance in its frame can do that is in the measuring device. So, this is your measuring device nowadays. So, now SMR is fitted hereay, spherically mounted retro reflector. So, basically, that is a spherical ball sort of thing that will be mounted here, so it is spherical. So, any light, if it comes to that, it goes back to the same direction. So, similar is the case of civil engineers, they do with 3D light apparatus also. So, this is what is your SMR. So, laser light is now falling from the FARO laser tracker, and that falls on this. So, now I am measuring the floor on which this is mounted.

The whole of this structure is mounted, and that is the FARO laser tracker and this is my robot. I am mounting it here. So, now it is fitted. Now you see, SMR is fitted here. Here is your SMR. That is the retro reflector. So, this point is basically tracked so that this point is nothing, but it is the replica of the point, which is also moved by the robot. Overall there is a payload also which is fitted hereay, so now this makes this system complete. Now I am free to move. The whole of the thing is now placed properly, and this is the FARO laser tracker closely shown here so that point will move.

This tracker will also move its laser pointer, and it will follow that pointer. So, now a programmer sits here, and he will command the robot to go to the plane, one of the planes of the robot. That is the cube arrangement that I have shown here, so this is the whole arrangement. So, this is how it is fitted, got it? So this is your SMR.



Now, I will show you a small video. So, you see the structure is moving, SMR is moving along with that. So, all the corners of the cube it is actually traced, starting from the middle point, and the FARO laser tracker will follow this point, record it precisely in its coordinate frame and that is used to calculate the repeatability.

So, hope you understand how this is actually done. So, with that, we'll end here, and in the next module, we'll continue with robot control. That's all for today. Thanks a lot.