NPTEL Online Certification Courses
COLLABORATIVE ROBOTS (COBOTS): THEORY AND PRACTICE
Dr Arun Dayal Udai
Department of Mechanical Engineering
Indian Institute of Technology (ISM) Dhanbad
Week: 01
Lecture: 02

Collaborative Modes, Contacts, Bio-Mechanical Limits, and ISO Standards

Hello, and welcome back to the course COBOT: Theory and Practice.
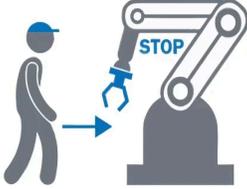
Overview of this lecture

- Collaborative modes: As per ISO Standards
- Power and Force Limiting: Quasi-Static and Transient Contact
- Biomechanical Limits for the onset of pain
- Safety standards
- Major Makers of COBOTS

COBOTICS: *Theory and Practice*   Module-01—Lecture-02   Arun Dayal Udai

In this lecture, I'll discuss various collaborative modes as defined by ISO. I'll discuss Quasi-Static and Transient Contacts. I'll discuss Bio-Mechanical Limits for the onset of pain as per ISO 15066 standard, various ISO standards that apply to a Cobot and major Cobot makers that are primarily reported in multiple research and production units across the world. Okay, so let us begin.

Collaborative modes
As per ISO 10218-2 and ISO/TS 15066

Monitored Safe Stop	**Speed and Separation Control**	**Manual Guidance**	**Power and Force Limiting (PFL)**
Robot operates autonomously, *pausing safely* for entering personnel. Uses: Light Curtain or Gate Switch	The robot adjusts its *speed depending on the distance* from the worker. No contact with the robot is allowed. Uses: Vision, LIDAR, or Ultrasound sensors.	The *operator guides the robot manually*, using it as a high-performance manipulator. Monitored safe stop is executed. E.g.: May have a button to release the brakes.	Safe human-robot contact: force is verified and powe... d. *COBOTS*... ve Impedance... ss

So yes, what are Collaborative modes? As per ISO 10218-2 and ISO/TS 15066, they are broadly classified into four categories. The first one is Monitored Safe Start kind of. The first one is Monitored Safe Stop. So, what is that? It is in this case the robot operates autonomously and it pauses safely for entering any personnel. So, it could be a standard industrial robot which is there in the industry which are position controlled. They are normally caged and it may have provision to detect human entering into the workspace of the robot.

It may use a safety curtain, light curtain or a Gate Switch if at all there is a fence and there is a gate; as soon as the gate is opened, it assumes the person is attempting to enter the workspace, and the robot stops safely without actually hampering the programming okay. If at all some cycle is going on, it will continue once the person goes out of the robot workspace okay. So, that is a monitored, safe stop. The second one is Speed and Separation Control. In this, the robot adjusts its speed depending on the distance from the worker. No contact with the robot is allowed. While the robot is moving, there should be absolutely no contact. What it does basically it uses a kind of vision sensor or a radar or an ultrasound sensor to detect the speed of the person who is coming towards the robot. So, as it goes closer and closer robot may gradually stop right. So, at a certain distance, it will run at a very slow speed. When it comes quite closer, in that case robot may totally

stop. The way it did it in monitored safe stop conditions. Right. So, this is the second way. Again, in this case, the robot could normally be a standard industrial robot, but there may not be any fence, or just temporary fencing is there right? So, that is the second case, and the third one is the Manual Guidance robot. In this case, the Robot is operated by humans.

The operator guides the robot manually, using it as a high-performance robot. Right. In this case, the person is able to take the robot to a certain place manually by pressing a kind of button that releases the brakes, and it allows humans to drag the robot to a place. That is normally useful in programming, reprogramming or maybe doing tool teaching and that kind of maintenance stuff. So, this is, again, a standard industrial robot.

Not many safety guidelines are followed here, apart from standard industrial safety guidelines and robot safety guidelines. That's all. Cobot is not there in the picture still. So, this is a standard industrial robot that allows doing so.

And the fourth one, which is the final one, is Power and Force Limiting (PFL). So, in this case, safe human-robot contact is established. In this case, humans and robots they are in contact with each other. Force is verified before it is being applied, and it is limited by the power at the joints, the power that goes at the end effector so that humans, whosoever comes in contact with such robots, are safe as per Cobot standards. So, these are standard Cobots.

It may have an Impedance Stiffness Controller at the joints or at the end effector level. Okay. So, this one is actually a Cobot. So, that is what. So, even PFL, any standard Cobot may also allow manual guidance, and this also can take any of these into account as well because just having a Cobot, there is an assumption that your workspace is 100 percent safe. It is never the case; you may still have to follow monitored safe stop in certain cases. It depends on application to application, basically. So, these guidelines are still followed right. Apart from this being a PFL robot like a Cobot So, that is the case. So, there are a total of four types of collaborative modes are these.

► The robot system shall be designed to adequately reduce risks to an operator by not exceeding the applicable threshold limit values for **quasi-static** and **transient contacts**, as defined in Annex A, ISO/TS 15066:2016 (E)

► *Contacts*: Could be Intentional, Incidental, OR due to a Failure.

Quasi-Static contact

► Contact duration: Long

► Limiting criteria: Peak pressure and forces (stress)

► The body part gets clamped between the part of the moving robot and another fixed/moving part of the robot cell.

So, what is PFL? Basically, this, in short, is known as PF and L, Pressure Force Limiting. We will also learn about Quasi-Static and Transient Modes. I will also discuss Quasi-Static and Transient Contact here. The robot shall be designed to adequately reduce risk to an operator by not exceeding the applicable threshold limit for quasi-static and transient contacts as defined in Annexure A, ISO/TS 15066:2016 (E). okay. So, mind it, all the standards that I am showing here over here it is 2016, that is the year in which it was published. So, it is revised in a timely manner every five years, normally okay. So, it may change over time, and all these definitions and a few modifications could be there without your notice. Right.

So yes, That is to be noted down here. So, what are Quasi-Static and Transient Contact? What exactly is contact, first of all? So, contact could be due to an intentional operation. It may be trying to measure something. Right. You take your robot to some place, and you want to measure the coordinate or forces or something. Right, or maybe due to teaching. So, that could be intentional. It could be incidental. You have programmed to do something, and then it overshoots it, or it did something primarily because of program failure or something like that, and the third one is due to the total failure of the robot. Let's say one of the joints totally failed; it breaks, collapses, or in those cases, the robot may freely fall or some kind of such thing. So, those contacts are also ther,e but yes, in all

these these contacts. as far as the Cobot is operational then, only it is defined. It may be a failure in programming. It may be a failure of one of the joints. In all the possible cases, it has to follow Quasi-Static and Transient Contact forces, which are defined next.

So, what exactly is Quasi-Static Contact? This type of contact is normally for a longer duration. Limiting criteria are peak pressure and forces that actually produce stress on the person with which it is in contact. Right. The body part gets clamped between the part of the moving robot and another fixed or moving part of the robot cell. Over here, it is shown hand is getting trapped. It is clamped between the table and the robot two fingered gripper. The person cannot move out his hand. So, this is one of the cases.

It could be possible that the robot has clamped you against the fence. So, that could be another case. So, this is basically Quasi-Static Contact.
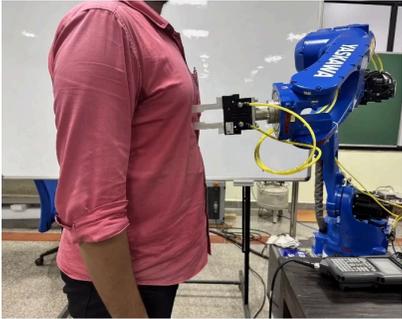
The next one is Transient contact. In this, the contact duration is less than 0.5 seconds. The limiting criteria are, again, Peak pressure and the forces that are to be controlled. Energy transfe, this is an additional thing that has to be taken care of also. This basically is the power density that goes into the robot when it does such tasks, right? So, not necessarily a task; it may be due to incidental, or it may be due to the failure also. The body may recoil or retract from the moving part of the robot. Over here, you see, there is

a pretty good amount of space at the back of the person. He may come out of the robot workspace totally. So that way. So this is known as a Transient Contract. Okay.

So, now total Biomechanical Limits are there for the onset of pain. This pain is also defined in ISO/TS 15066:2016 (E). So, it has split the body into 29 body areas. The maximum allowable pressure in the case of Quasi-Static Contact is 110 to 300 Newton per centimeter square.

This is as per Quasi-Static Contact, and the maximum allowable force is 65 to 220 Newton, depending on which part of the body it is. The same in the case of transient contact, it is maximum allowable pressure multiplier is there, and over here, it is 2 times, except for the transient contact should not happen in the head areas, okay? The areas that are related to the head, like the face or, forehead or skull, like that okay, and the same maximum allowable force multiplier is two times for except for the head area. So, this limits all these biomechanical limits were estimated by three repeated tests on a hundred healthy adult subjects. This was a project that was done at the University of Mainz, Germany, in 2014, and you can find it out FP-0317 report is there. I have referred to it here.

So, yes this is the normal operating region of the Cobot. Normally, it should it is favorable. You should work in this region. If at all it establishes the contact, it gets into the region of pain. So, as soon as the contact is established, this whole region is for the pain. The pain has already started, and there comes a threshold over here. In this case, if it goes beyond that threshold, injury can happen. It may be a minor injury; it can be reversible, and it can be an irreversible injury as well. So, the threshold remains till here only. So, the onset of pain is defined as per ISO 15066. This is adapted by the study which was conducted the University of Mainz. So, this is it.

So, this is the body model which has actually split the whole of the body into 29 body areas. So, this you can refer to this here. This is the link I have provided. So, this is the frontal portion of your head that, is the forehead that is the temple area. The skull area is here, and you have a face, you have a neck, okay? So, you see, there are skull and a forehead; there are two locations. Face, there is one. Neck, there are two. Back and shoulder, two. Chests, another two. Abdomen, pelvis, one each. The upper arm, and the lower upper arm and elbow joints there are two. Lower arms and the wrist joint, there are three. Hands and fingers, there are nine. Actually it is dominant as well as non-dominant contact points are there. So, that is why it is nine over here. Thighs and knees, there are two, and lower legs, there are two. So, all together, there are 29 contact points which are

studied. So, this is all about the Quasi-Static Contact. Mind it there is no separate study that was conducted for transient contact. So, the values which are shown here in this table are basically, there is no research and are based on conservative calculations. Pressure and force limits for transient contacts are established by curves for the onset of pain for various body parts, right? So, these are basically out of conservative values, and they are made out of some kind of estimation, and there is no detailed research which was done for these regions, right? So, this are very conservative values, mind it. So, only for this, there are studies which were reported, right?

Safety standards

Standard	Description
2006/42/EC	Machine Directive
ISO 12100	Safety of machinery — General principles for design — Risk assessment and risk reduction
ISO 10218-1	Robots and robotic devices: Safety requirements for industrial robots — Part 1: Robots
ISO 10218-2	Robots and robotic devices: Safety requirements for industrial robots — Part 1: Robot systems and integration
ISO/TS 15066	Robots and robotic devices — Collaborative robots
ISO 13855	Safety of machinery — Positioning of safeguards with respect the approach speed of parts of the human body

*This is apart from other Industrial Robot standards like ISO 9283: Performance Criteria, and ISO 13849: Safety of Machinery, e

So, what are the Safety Standards which a Cobot manufacturer has to follow? It's not just a Cobot standard, basically. So, these are a few. So, 2006/42/EC directive. So, that is machine directive basically and 12100 that is the ISO standard. It is for the safety of machinery, general principles for design, risk assessment and risk reduction. It is not just for robots. It is for any general machinery, and the same applies here, also ISO 13849, and, that is for the Safety of Machinery. So, this is not the only thing. There are many other standards which are followed. So, that's it and then ISO 10218-1 and ISO 10218-2, So, it is for robots basically and not just for machines, it is for robots. So, a robot also has to follow machine directives. So, robot and robotic devices, safety requirements for industrial robots, part 1 that says for the robot, and part 2 is for robot systems and

integration. It is for all the accessories that goes around the robot. It may be a gripper, it may be a turntable, it may be a linear rail and even for the safeties which are around, so, it has to take care of all those. So, it is basically very, very important for the integrators where whereas this one is for the manufacturer, right? And then comes the final two standards that are ISO/TS 15066 which is for robots and robotic devices. This exactly is for collaborative robots, and maybe industrial robots need not to follow this one, but definitely a Cobot has to follow all the above standards, and ISO 13855 this is for the Safety of Machinery positioning of safeguards with respect to the approach speed of parts of the human body. This basically talks about the approach speed. Right. So, that is there. All these are, apart from ISO 9283 that, are for the performance criteria of the robot that is to obtain maybe repeatability of the robot is basically tested based on this positioning accuracy, and that stuff are defined here.

So, the robot has to go through all these plus this (2006/42/EC, ISO 12100, ISO 10218-1, ISO 10218-2, ISO 9283), and Cobot has to go through all of these Standards. So, these are not just the one. There are many other standards machine standards that are followed by the robots, basically by the integrators and the manufacturers.

Major Makers of COBOTS
With best of them: Selected Features

COBOT	Payload Kg	Horizontal Reach mm	Repeatability mm	DoF
KUKA LBR iiwa 14 R820	14	820	0.1	7
Fanuc CR-35iB	35/50	1813/1643	0.03	6
ABB Single-Arm YUMI	0.5	559	0.02	7
Franka Emika Panda	3	855	0.1	7
Han's Robot Elfin S.141	3	832	0.03	6
Kinova Gen3	4	902		7
Omron Techman TM14	14	1100	0.1	6
DOBOT CR16	16	1223	0.03	6
Nachi CZ10	10	1300	0.1	6
Precise Automation PAVS6	7	770	0.03	6
Rethink Robotics Sawyer	4	1260		
Staubli TX2touch-90	20	900	0.03	
Universal Robots UR30	35	1300	0.10	
Yaskawa HC10XP	10	1200	0.10	
DLR SARA	12	1250		

So, what are the major makers for these Cobots? Who are the makers, basically? There are many established manufacturers which were already there who were manufacturing

industrial robots. They came in first of all is Kuka LBR. Actually Kuka LBR started Cobot making with DLR first that came up with Kuka iiwa standard. That was an adapted version of the DLR arm, 7.0 arm. The first KUKA LBR 5 kg version was there, and later on, it came up to a 14 kg version with a reach of around 820 mm. That is what you can see. So, it has a payload capacity of 14 kg. Mind it, these are some of the robots.

There are many other manufacturers as well. I have just listed down a few that are primarily reported by the researchers and industrial users. So, this is a few best one of them. So, it is a 14 kg payload, which is pretty good for most of the industrial robotic-related tasks. Not for huge payload carrying and all. So, this much is the reach, and that should be quite good enough. It is more than an arm reach of a human. Repeatability is 0.1 degrees of freedom is as good as a human with a redundant one degree of freedom, that is 7. So, that is there, and we will talk about degrees of freedom and repeatability those aspects later in our course also. So, yes repeatability; when we talk about repeatability, it is as per ISO 9283 only. But yes, you see, you find quite good repeatability is there in the case of industrial robots. But when it comes to Cobot, because they are flexed, they are compliant, you cannot expect much repeatability in the case of Cobot. So, that is the reason quite a lot of robot manufacturers they do not mention it only. They are good robots, but yes, they do not mention it because that is for a different purpose altogether. Like, for say, Kinova Gen3 or Kinova Jaco, which was also a version of them. So, they didn't mention this because it may have a very poor repeatability. But yes, it is not meant to do maybe precise industrial tasks. It may be for a wheelchair-mounted robot when a human tends to do some kind of domestic stuff. In that case, that is always a human-in-a-loop kind of operation, and that is not very significant. FANUC It is one of the largest capacity Cobot that it is making with a very good reach also. And repeatability is reasonably very good. It is at par with the standard industrial robot. It is 6 DoF. ABB YUMI. It's a single arm that I have mentioned here, but there is also a dual-arm version. Franca Amica Panda is there. That is a 3 kg payload. Okay, repeatability is 7 DoF. Right. And then quite a popular one may be Rethink Robotics. There is Baxter also, which is there. It is a 4 kg payload. Baxter is dual arm.

Sawyer is a single arm. This doesn't mention its repeatability. Again, it's a 7-DoF robot. Universal robot. Universal robot, it is very, very popular. It is UR30 I have listed here. It has a 35 kg payload capacity. There are many other academic versions of UR5E, and that is quite a lot of places in research papers I have seen it, and yes, this also has a repeatability of 0.1, which is quite good. It is a 6 DOF.

DLR SARA is in one of the most advanced tasks is reported by this DLR SARA. For touch-sensitive robots, it is reported in 2024 only. So, it has a very good payload capacity as well as a good reach. Yes, it does not mention its repeatability, but it is a 7 DoF robot. So, these area few popular industrial Cobot makers. Okay, there are many others. So, yes.

So, yes, in today's class, you have learned about Biomechanical Limits. You have learned about various standards, Collaborative Modes, right? So, that's all for this lecture.

In the next lecture, we'll be discussing on the process of Risk Assessment, why it is important, and how it is done as per ISO 10218-1 and 2. That's all for today.

That is all for this lecture. Thanks a lot.