Robotics: Basics and Selected Advanced Concepts
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Lecture - 02
Main Elements of a Robot

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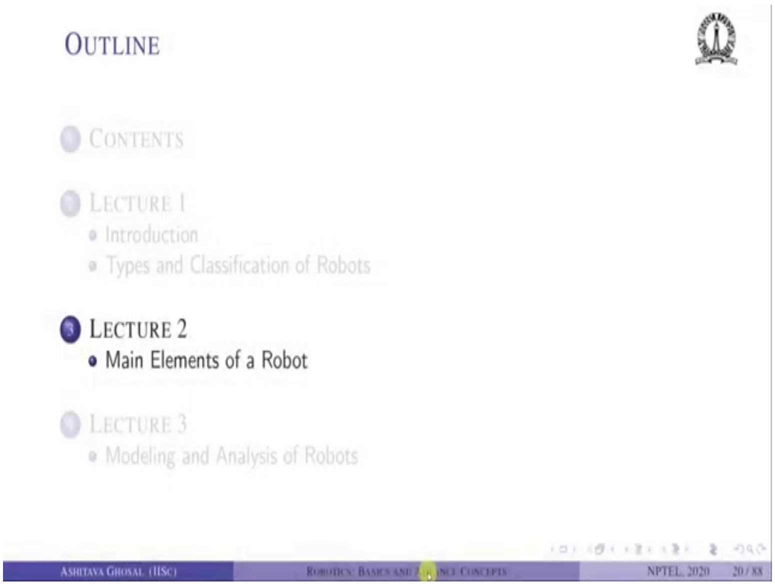

Welcome to the NPTEL lectures on Robotics Basic and Advanced Concepts. In the last lecture, I had introduced the various topics in robotics, basically little bit of history, little bit of how they are classified, and then I have shown you some videos of some well-known robots. In this lecture, we will look at the main elements of a robot.

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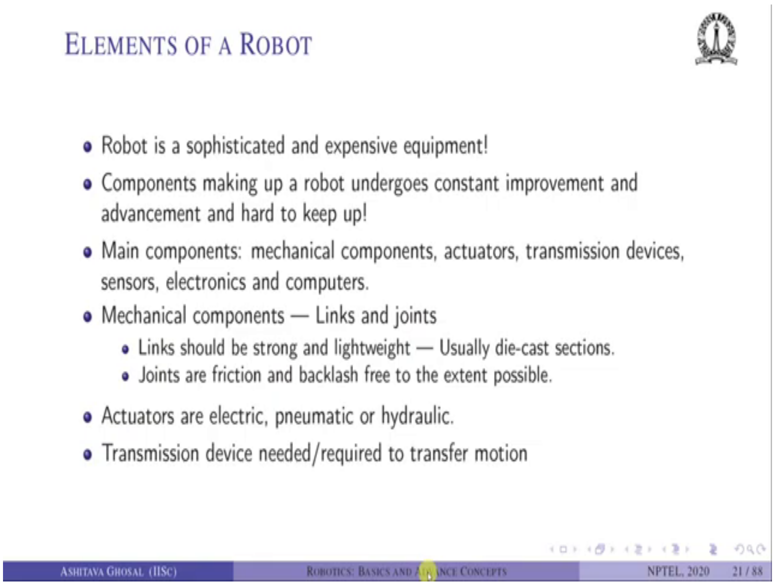

So, a robot is a very sophisticated and expensive equipment even now, ok. So, the components making up a robot undergoes constant improvement and advancement and it is very hard to keep up. So, initially the motors had some specification, now they are much better similarly there were some sensors which you had used earlier now they have much better sensors. So, it is sort of hard to keep up with all the various mechanical electronic and computer or sensing components which go into making up a robot, ok.

The main components are mechanical components, actuators, transmission devices, sensors electronics and computers, ok. These are the some of the key components which go into making a robot. The main mechanical components are links and joints, ok. So, link is basically the member, which carries the load, which moves, which positions something or other at the end of the link.

The links should be strong and lightweight, ok. So, most of the time they are very lightweight because they are made using die cast sections, ok, made up aluminium many quite often. The joints should be friction and backlash free to the extent possible, ok. Because if you have friction and backlash, the joints will introduce errors, which sometimes the controller cannot overcome.

The actuators are typically electric pneumatic or hydraulic, ok. And transmission devices are needed to transfer the motion from the actuators to the joint in a proper manner.

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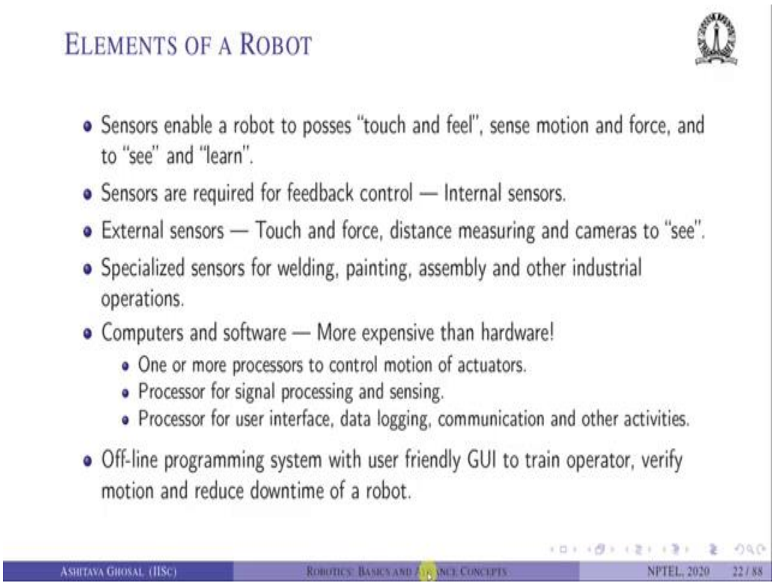

So, we will look at all these components, we will look at links and joints, we will look at actuators, we will look at transmission devices, and then we will also look at sensors, ok. The sensors enable a robot to possess touch and feel, sense motion and force, and to see and learn, ok. Sensors are required for feedback control, these are sometimes called as internal sensors.

There are also external sensors which you can sense touch and force, you can measure distances, and you can have cameras which can see the environment, ok. There are also some specialized sensors for welding, painting, assembly, and other industrial operations, ok. So, we need to make sure that the weld bead is correct height and we can change some parameters automatically or you can see that the welding is happening at the right place. So, those are very specialized sensors.

The computers and software which go into a robot are often more expensive than the hardware, ok. We have one or more processes to control the motion of the actuators. We sometimes have processors for signal processing and sensing. We also have processors for user interface, data logging, communication and other activities. So, typically in a robot you have a lot of computing power, and there is a lot of software which have been ported on to these computers to do a variety of tasks, ok.

We also have offline programming system with user friendly GUI to train operator, verify motion and reduce downtime of a robot. So, basically since the robot is so expensive, we do not want it to be lying idle and we do not want the robot such a robot to be used for training, ok. We would like to train the operator in a virtual environments which is that is what is called as the offline programming system. So, we have a CAD model of the environment, we have a CAD model of the robot and we can make this robot move, and train operator in this virtual environment.

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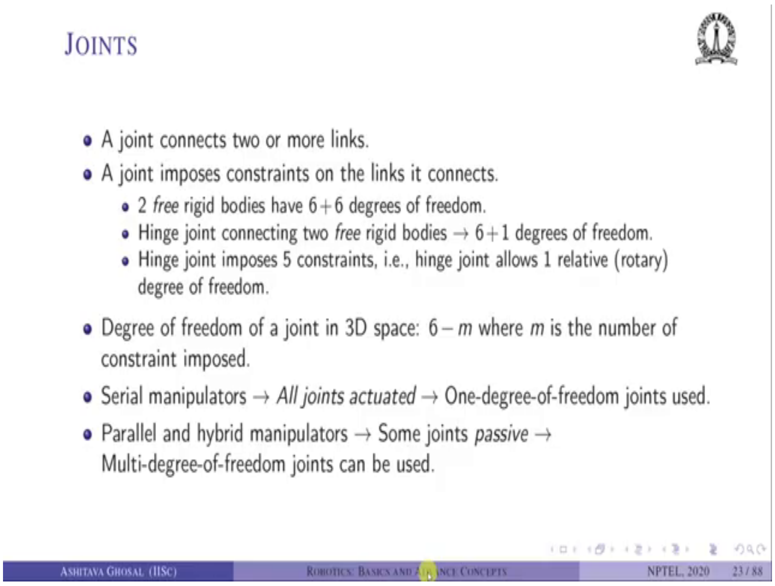

Let us continue. As I said we will look at joints links, actuators, transmission devices, and sensors in this lecture. So, what is a joint? Joint is nothing, but an element which connects two or more links, ok. So, basically what does a joint do? It imposes constraints on the link it connects. So, if you have two rigid bodies in 3D space, you have 6 each of them with 6 degrees of freedom. So, you have 12 degrees of freedom.

If you will now connect these two rigid bodies using a hinge joint, hinge joint is nothing, but one which allows rotation or relative rotation between the two connected rigid bodies. So, in that case then you have 6 plus 1 degree of freedom. So, basically what has the hinge joint done? It has removed 5 degrees of freedom. So, it has imposed 5 constraints, ok.

So, hinge joint allows one relative degree of freedom. So, we will look at these constraints and more detail in the lecture on kinematics of serial robots, ok. And before that and in the second week when we discuss mathematical representation of links and joints in more detail.

The degree of freedom of a joint in 3D space is 6 minus m, where m is the number of constraints imposed. So, for example, a spherical joint or a ball and socket joint will impose 3 constraints and the degree of freedom is 6 minus 3, which is 3, which very easily known or can be very easily seen. In a serial robot all the joints are actuated, ok. And most of the time 1 degree of freedom joints are used, ok.

In a parallel robot or in a hybrid robot some joints are not actuated they are called passive joints and those passive joints can be multi-degree-of-freedom joints. So, for example, in the Stewart platform which I showed you in earlier in the last lecture there were these spherical joints, but they were not actuated, there was a Hooke joint and then that was also not actuated. So, only actuated joint was the sliding joint.

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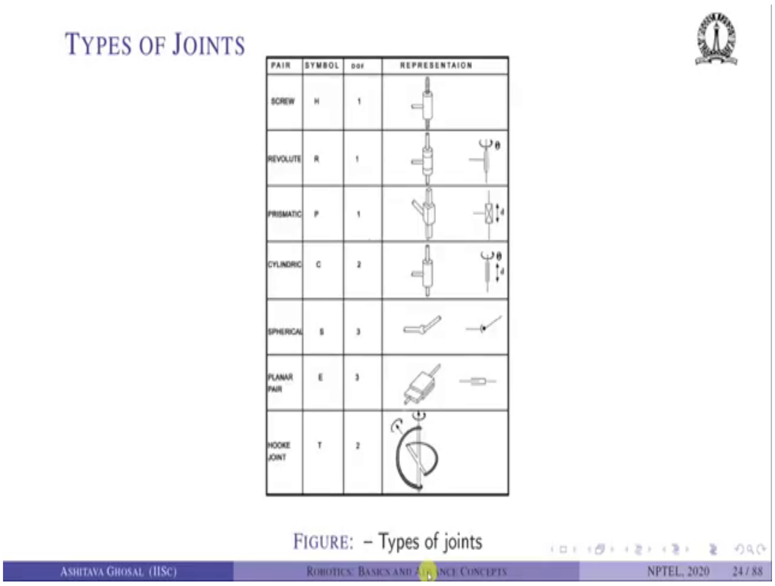

These are some of the typical joints which are in use in robotics. Screw joint, not so common, but sometimes it is used. So, basically you have one member which is the shaded and one member which is the white portion. The white portion can rotate and translate about this screw access you just like a normal screw. It is a 1 degree of freedom joints simply because the rotation and the translation are related by the pitch of the screw.

You also have rotary joint it is 1 degree of freedom joint. Again we have two members, just like a hinge joint and the second member can rotate with respect to the first member. So, this is θ is a typical variable which is used to denote a revolute joint.

We also have prismatic joints, where one member and slide up and down this other number, and the variable which is used to denote the sliding motion is d typically. We have a 2 degree of freedom cylindric joint which are sometimes seen in closed loop mechanisms, where this θ rotation and this sliding d are not related, there is no pitch, ok. They are independent.

As I said you can also have a spherical joint, it has 3 degrees of freedom. Spherical joint is nothing, but a ball and socket joint. And these are this is another theoretical joint which is called as a planar joint. So, basically you have two planes and that is relative 3 degrees of freedom between these two planes, ok. The second object here can slide in the X and Y direction, and also rotate with respect to the other object.

And we have a Hooke joint or universal joint where you can have 2 degrees of freedom about two independent axis. So, these are some of the common joints which are used in robots and in some closed loop mechanisms and parallel manipulators.

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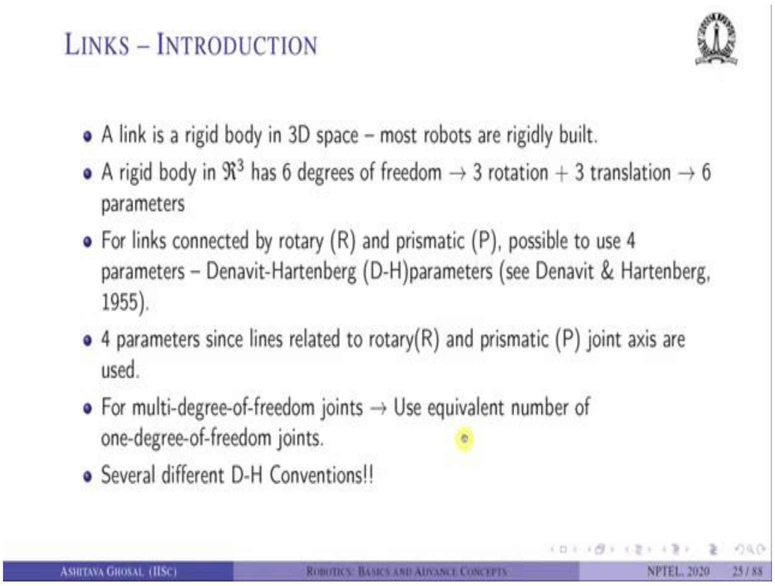

Let us continue. A link is a rigid body in 3D space, ok. As far as we are concerned in kinematics, dynamics and control, most of the time in control. It is a rigid body in 3D space, ok. Most robots are rigidly built.

We will not look at the deformation or the deflection of a link. If you are interested in the space shuttle now then we need to worry about the deflection, then the link is no longer rigid, ok. And we have to introduce this deformation and deflection of the members of the robot.

A rigid body in 3D space has 6 degrees of freedom, so it can rotate about 3 axis. So, there are 3 rotation degrees of freedom and there are 3 translation degrees of freedom. So, it requires 6 parameters, ok.

So, a link of a robot would require 6 parameters in general. However, if the links are connected by rotary and prismatic joint it is possible to use 4 parameters only to describe the relative motion of one link with respect to another link, or describe one link with respect to another link.

So, these are known as that Denavit-Hartenberg parameters, ok. And they were invented by these two researchers Denavit and Hartenberg in 1955. So, as you can see this is very useful because almost for the last 65 years, they have survived. If something is not useful then it would have died a long time back. And the basic reason why it is useful is I do not want to carry around 6 parameters, if I can get away with 4. It is two-third less. So, an in robot you have many rigid bodies.

So, you can see that if you have 6 rigid bodies connected by joints we do not need to worry about 6×6, 36 parameters; you can away with 24, ok. So, these 4 parameters are possible since lines are related to rotary and prismatic joints are used, ok. So, we will look at in the kinematics portion of this robotics course. What are the DH parameters? And how to find the DH parameters? Ok. What are the exact definitions of each of these 4 DH parameters?

For multi-degree-of-freedom joints if you have a multi-degree-of-freedom joints and you want to use these DH parameters then you have to replace this multi-degree-of-freedom joints with 3 or more or multi- more than 1 degree of freedom joints, ok. So, for example, if you have a spherical joint with 3 degrees of freedom you can use 3 equivalent rotary joints, ok. So, this is a good thing to do.

So, this is a very nice approach. It has a lot of advantages. We can get role which 4 parameters. Unfortunately, there are several DH conventions possible, ok. And many textbooks will have one way to describe the DH parameters and some other textbooks will have another way to describe this DH parameters, ok. It turns out that is what happens when you go from 6 to 4, you have several possibilities. We will be using the DH convention which is there in my book or it has actually borrowed from the book by Craig a very well-known book, on robotics.

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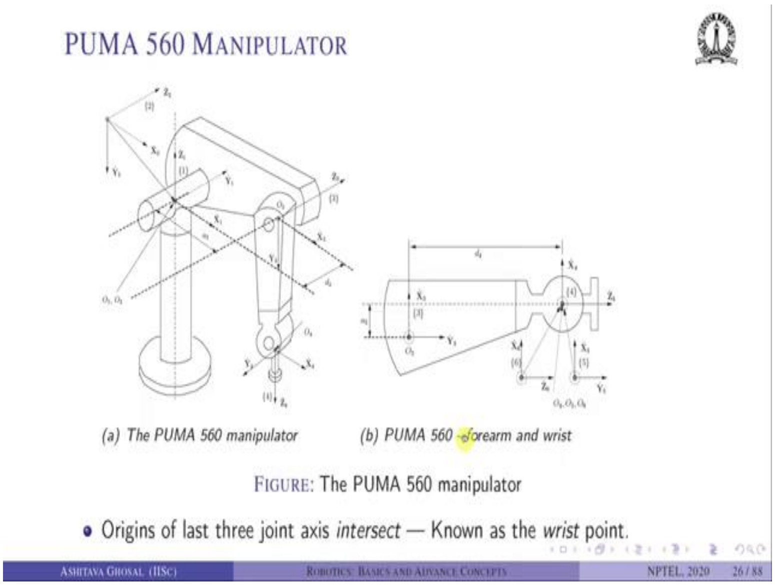

So, let us look at the robot. What do we really mean by? How do we really describe? This is a very brief introduction. We will look at all these things in much more detail in the second week. So, in this PUMA robot we have 6 joints. So, one rotary joint is here where my cursor is, one rotary joint is perpendicular to that vertical joint. There is a third rotary joint here; so, most of the time we will see Z_1, Z_2 or Z_i denoting the joint axis, ok.

And then there are these three rotary joints which are intersecting at this point this is also sometimes called as the wrist point. So, we have Z_4, Z_5, Z_6 which are intersecting at the same place. And as you will see in more detail later the DH parameters are these distances a_2, d_3, a_3, d_4, and so on, ok. These are link length link offsets. And you will also have some wrist angles.

So, the angle between joint 1 and joint 2 is one such parameter. In this case it has been built with 90 degrees, ok. Built so that, they are at 90 degrees to each other. So, you will have all these 4 parameters which we will describe in more detail next week. Interesting thing in this design is that the last 3 joint axis intersect at one point, and this gives a lot of advantages in the modelling and analysis of this robot, especially in kinematic analysis, ok.

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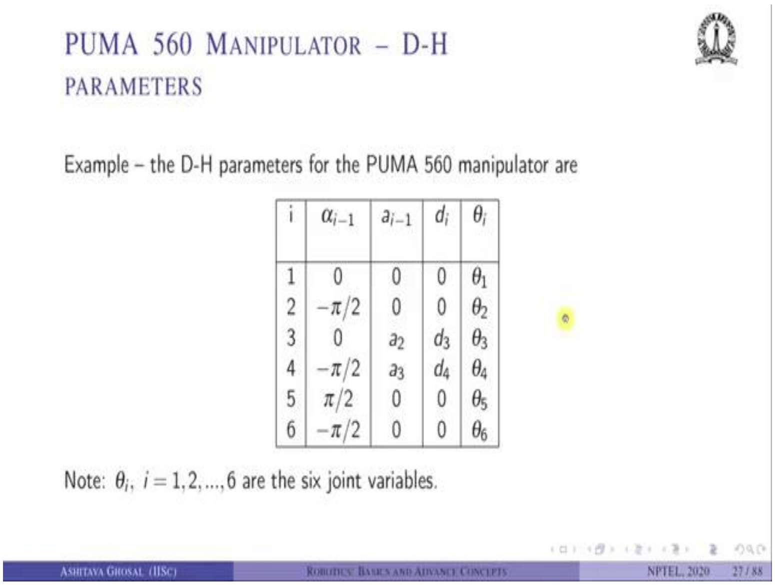

So, as I said there are these 4 DH parameters, most of the time these 4 DH parameters are given in the form of a table, ok. So, in this table what you have is i, it is the link numbers, so these are 1, 2, 3, 4, 5, and 6. The PUMA has 6 links.

And along the row you have this α_{i-1}, a_{i-1}, d_i and θ_i. So, these are the 4 DH parameters for each link. So, for example, of the third link α_{i-1} is 0, a_{i-1} is some quantity a_2, it is a number, its a distance; d_i is d_3 another distance and θ_i which is a rotation of the third link, ok. It is a joint variable.

So, in this PUMA all the joint variables are rotary, joint variables which are represented by θ, ok. I discussed this I told you earlier. So, we have θ_1 to θ_6, as a 6 joint variables. As you can see in this DH table many of the α's are very simple it is either 0 or $\pm\pi/2$, ok. And that is how most robots are designed and built, ok. It could have been 30 degrees, 22 and a half degrees, but normally as a designer we pick these nice simple parameters, ok.

When you buy a robot you will get a table like this, for any robot and basically they will give you the DH table for that robot. So, if you have a 6 degree freedom robot you will get a table with 6 rows. If you have 4 degrees of freedom robot you will get a DH table with 4 rows, ok. This is supplied by the manufacturer who in turn has obtained it from the designer.

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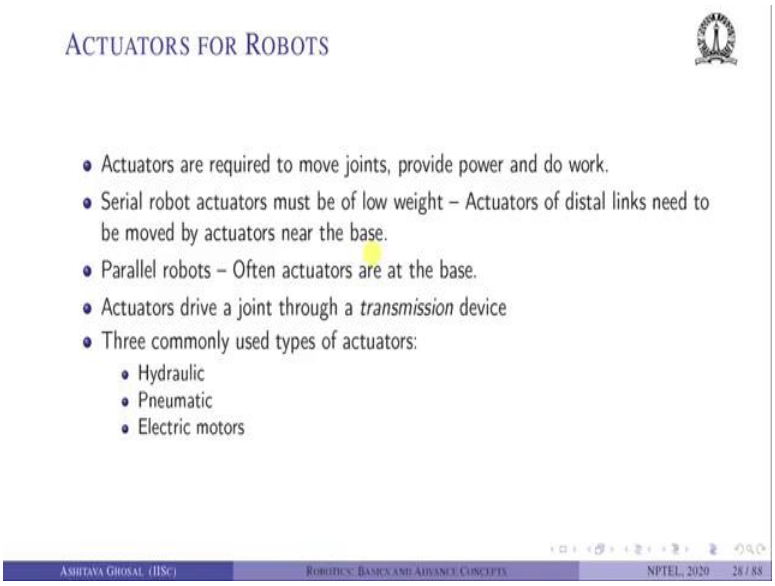

Let us continue. The actuators are required in a robot to move the joints to provide power and to do work, ok. In serial robot, actuators must be of low weight, ok. Why? Because the actuators of the far away links the distal links need to be moved by the actuators near to the base, ok. So, that is in the case of the PUMA robot.

The actuator which is driving this 4th joint, must be moved by the first joint. So, if you have a very heavy actuators sitting on this 4th joint, the first joint will have to do lot of work, ok. It has to put in a lot of effort, it needs to be very powerful. So, we need actuators which are lightweight and of high power, ok. The actuators the distal links need to be moved by actuators near to the base. In the parallel robot often actuators are at the base. So, we do not really have to worry too much about moving another actuator.

The actuator drive a joint through a transmission device and we will come to that, ok. So, the motor most often is not directly connected to the rotary joint. There will be some in between device which is called as a transmission. And there are three main types of actuators, hydraulic, pneumatic and electric motors.

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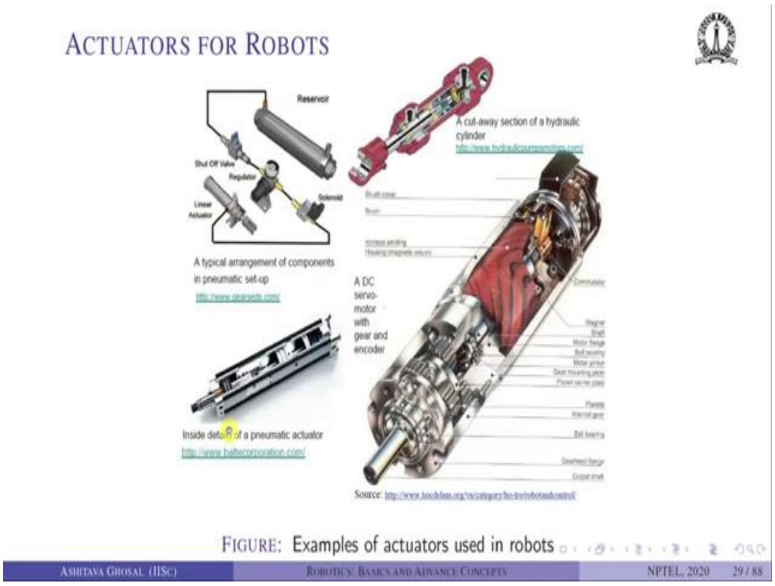

So, these are some pictures of typical actuators. So, on the top left where my cursor is this is a pneumatic actuator. So, basically in a pneumatic actuator we have some reservoir where compressed air is kept then you have some kind of valve, then you can have some kind of a regulator and a solenoid, and then this let us in the air into this actuator. So, when air is let in this end will go in and out. Sometimes you have inlet at two places one to send it in one direction and one to send it in the other direction, ok.

The hydraulic actuator is something very similar except instead of air you have compressed oil, ok. So, hydraulic actuators can transmit much more force, it has and transmit much more power, because air is light and it is compressible whereas oil or water is incompressible. We can also have a DC motor, ok. So, this is a nice picture of a DC motor showing all the parts.

So, basically what do we have a rotor which is not really seen here, which is a most of the time a permanent magnet, and then on top of that we had the stator which is coils, ok. So, we sent current to this coils and due to Faradays law, the rotor which is permanent magnet will start rotating, if the direction of the currents are changed.

We also have a device which is called as an encoder, which will measure the rotation of this rotor shaft because in control we need to know how much is the motor rotating. Finally, we also need to somehow reduce the speed of this rotor shaft, ok. In typically a motor will rotate very fast maybe 2000 rpm. You cannot connect the shaft of the motor directly to the joint. So, there is most of the time there is some kind of a transmission device. In this case, what is shown is a gearbox which will reduce the speed of the output shaft.

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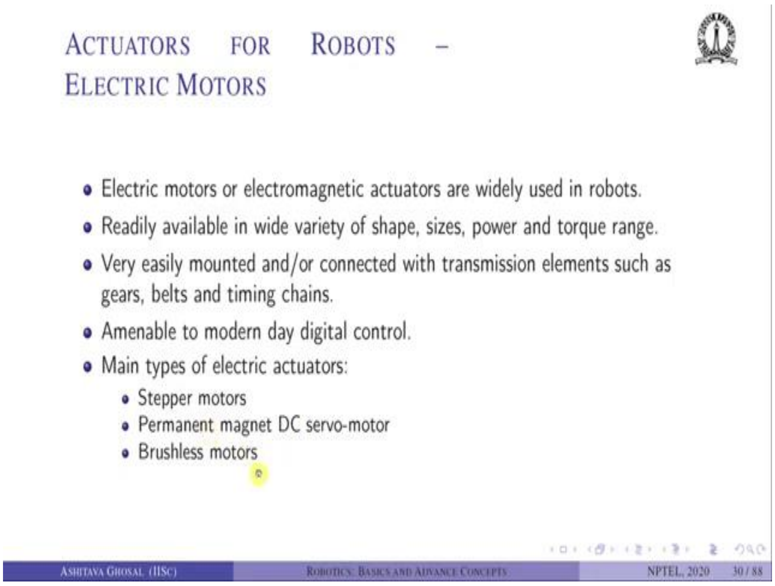

So, the electric motors or electromagnetic actuators are widely used in robots. They are readily available in wide variety of shapes, sizes, power, and torque range. They can be very easily mounted or connected to the transmission elements such as gears, belts, and timing chains, ok. They are also amenable to modern day digital control, ok. So, they have an encoder which measures the rotation. And we will see later that this measured rotation of the shaft can be used to control the rotation of the motor shaft or the speed of the motor shaft, ok.

There are 3 main types of electric actuators which are been used, one is called stepper motors, one is permanent magnet DC servo-motor and there is something called brushless motors, ok. In a brushless motor, the currents are not switched in the direction you want, by means of brushes which it is done electronically.

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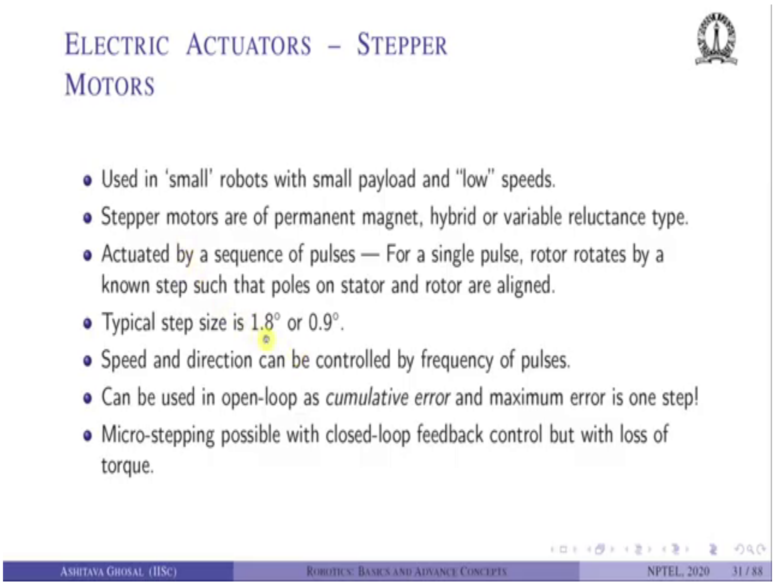

The stepper motor is normally used in small robots its small payload and low speeds, ok. Stepper motors cannot provide too much torque or cannot operate at very high speeds. Stepper motors are typically permanent magnet, hybrid or variable reluctance type, ok. So, these are some terms which are common in stepper motor literature, ok.

A stepper motor is typically actuated by a sequence of pulses, ok. So, for a single pulse, if I give a single square wave a single pulse then the rotor will rotate by one step, ok. And how much does it rotate? So, the steps are such that the rotor and stator will become aligned at the end of the step. So, the typical step sizes in stepper motors at 1.8 degrees or 0.9 degrees.

So, every time you give a step it rotates by 1.8 degrees or 0.9 degrees, ok. And the speed and direction of this stepper motor output shaft can be controlled by the frequency of this pulses, ok. So, if you want to rotate very fast you get these pulses at a higher frequency. One of the advantage of a stepper motor is that it can be used in open-loop, ok. Why? Because there is no cumulative error; the maximum error in a stepper motor is typically one step.

So, it will be maximum of 1.8 degrees or 0.9 degrees depending on the step size in the stepper motor. A stepper motor can also be used in micro stepping mode, ok. So, basically what is micro stepping? We do not want 1.8 degrees, but let us say we want one-tenth of this, 0.18 degrees. So, this can be achieved and for that we need closed loop feedback control, ok. And when you do micro stepping there is a loss of torque in the stepper motor. Most of the time stepper motors cannot provide large torques and in micro stepping that output torque is even smaller.

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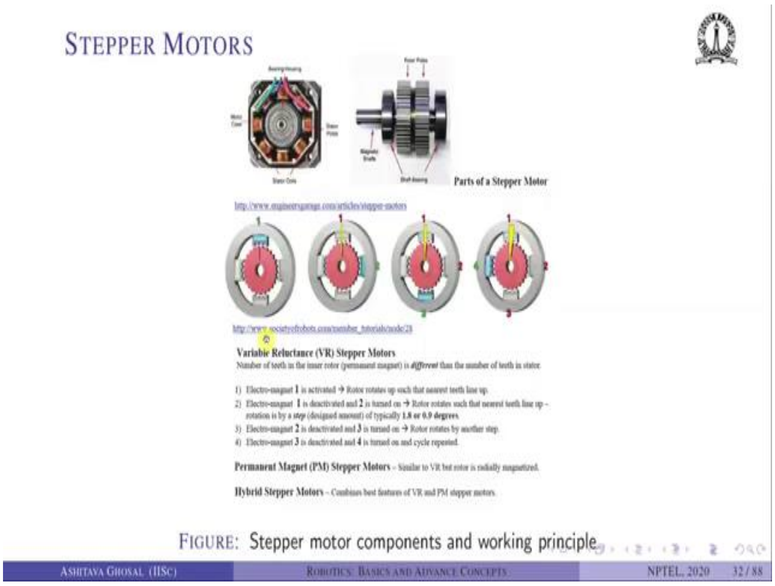

This is a typical picture of a stepper motor, ok. So, there is a rotor which contains all these teeth, then there is a casing, motor casing, and then there are the stators with coils, ok. So, schematically, what is shown here is, the rotor with number of teeth which are magnets and the stator which are coils. So, basically what happens is if electromagnet 1 is activated the rotor rotates such that the nearest teeth lineup, ok.

If electromagnet 1 is activated or deactivated and 2 is activated, then the rotor rotates such again the nearest teeth lineup, and this rotation is by a step which is typically 1.8 or 0.9 degrees. If 2 is deactivated and 3 is turned on, again it will rotate by one step again till the teeths line up, and so on. So, it keeps on activating, and deactivating, and at each time there is a step which is done, ok.

So, a permanent magnet stepper motor is similar to this variable reluctance stepper motor. This is the variable reluctance stepper motor which is shown, except the rotor is radially magnetized, ok. So, instead of these teeth or magnetized teeths, we have this radial magnetization. And we can also have hybrid stepper motors which basically combines, the best features of variable reluctance stepper motors and permanent magnet stepper motors, ok.

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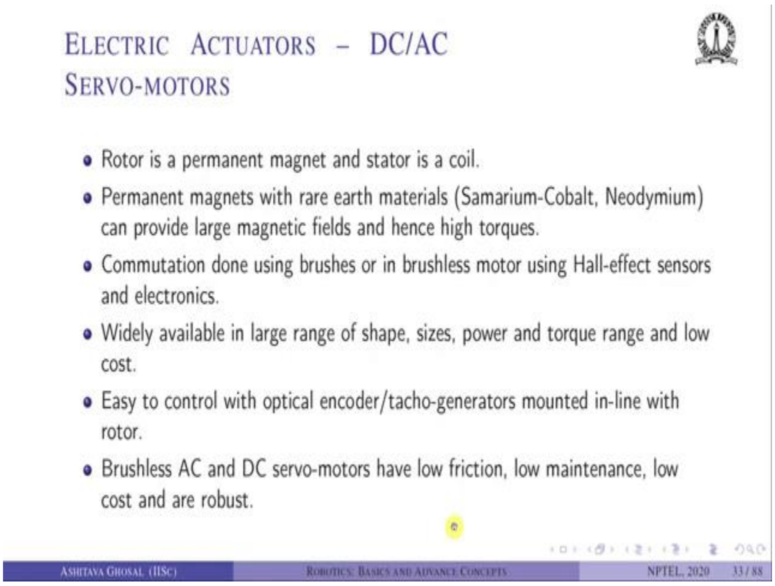

So, we can also have DC or AC servo-motors. A rotor is a permanent magnet again and the stator is a coil. The permanent magnets are typically made with rare earth materials, ok. So, there are these samarium-cobalt, neodymium, and various other rare earth materials which can be used to make very strong magnets, which can get very powerful magnetic fields and hence you will get high torques.

Commutation is done using brushes or in brushless motor using hall-effect sensor and electronics, ok. As I said if you have brushes, brushes then this is the standard DC motor, ok. You change the direction of the current because the brushes work in that way you can also do this commutation using this Hall-effect sensors and electronics these are called brushless motors.

A DC actuator, a DC servo-motor actuators are widely available in large shape, sizes, power, and torque range and these are very very reasonable nowadays, ok. Its also easy to control because most of them come with the optical encoder or we can fix an optical encoder at one end. You can also attach a tacho-generator which mounted in line with the motor shaft, and then we can measure both the rotation as well as the velocity the speed of this motor, ok.

The brushless AC and DC servo-motors have very low friction because there is almost nothing in contact. They are also very low maintenance, there low cost and robust, ok. So, most of the time nowadays the trend is to use this brushless DC motors. Also sometimes called as BLDC motors.

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So, here are some of the pictures of some of the well-known DC motors out of which this is an interesting motor. These are called small RC servo-motors, ok. These are toy motors that these were originally made for remote control toys, RC, that is why the word RC comes from. And they are easily available in internet. These are some very well-known companies like pittman and there is also some other companies which make these DC servo-motors, DC brushless motors.

This is another interesting DC motor, ok. This is what is used in electric bikes and cars. So, most of the time we have seen that the rotor is inside and the stator is outside; so, we provide current to the stator and that inside rotor rotates. In a bike, electric bike we invert it. So, the stator is inside and the rotor is outside. So, we provide current to the stator and the rotor is basically on which a wheel is mounted.

So, as you can see this is looks like a hub, and we can mount the wheel on top of this and when you provide current to the stator now, the rotor which is outside will rotate, ok. And they come with variety of ranges which you can get some 48 volts, 24 volts, 60 volts, various kinds of DC voltage which needs to be applied and then the wheel will rotate, and they can be directly used in electric bikes and even nowadays in cars. This is also sometimes called as the hub motor. Why? It directly fit into the hub of your bike.

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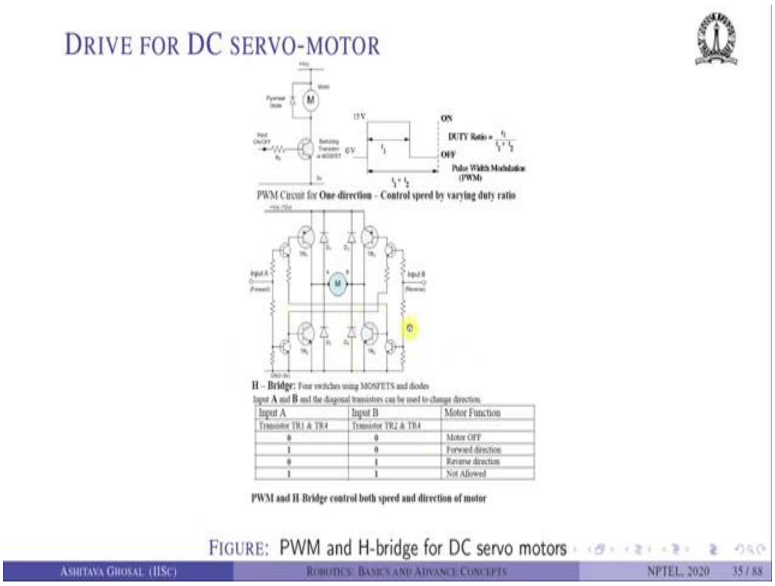

How is the DC servo-motor normally driven? Basically, what we have is we have what is called as a PWM circuit, ok. So, what is a PWM circuit? We provide a pulse of 0 to between 0 and 12 volts, and we modified the width of this pulse, ok. So, for example, if it is on for t_1 and it is off for t_2, we will get some average voltage, ok. If it is on for full length of time then you will get 12 volts which you are applying to the terminals of the motor.

So, this quantity t_1 divided by t_1 plus t_2 is called the duty ratio and by changing this duty ratio we can give a different average voltage to the motor, ok. And this step is done at a very high frequency. So, the advantage of this is that we are only not changing the actual voltage we are applying, but we are changing the duty cycle electronically. So, that is why this is called as Pulse Width Modulation, ok.

The way to drive a DC motor is basically using something called as a H-bridge, ok. So, we have transistors and we have an input which is forward and reverse two inputs, and then we have this arrangement which looks like a bridge H-bridge, ok. So, if the part, if the input is 0 and this is also 0 the motor will be off. If the input A is 1 and the input B is 0, then the motor will rotate in the forward direction.

The current will go such that the motor will rotate in one direction. If you switch the order of the input and make A as 0 and B as 1, then you go in the reverse direction and you cannot have both inputs. So, basically what you are doing is by switching input A and B to 0 and 1 again using digital control the whole idea is we want to do everything digitally, then we can make the motor go forward, backward, or be off, ok.

So, these two things enable a DC motor to be controlled electronically. You can control the speed by modulating the width of the pulse and we can change the direction by switching between the two inputs, ok.

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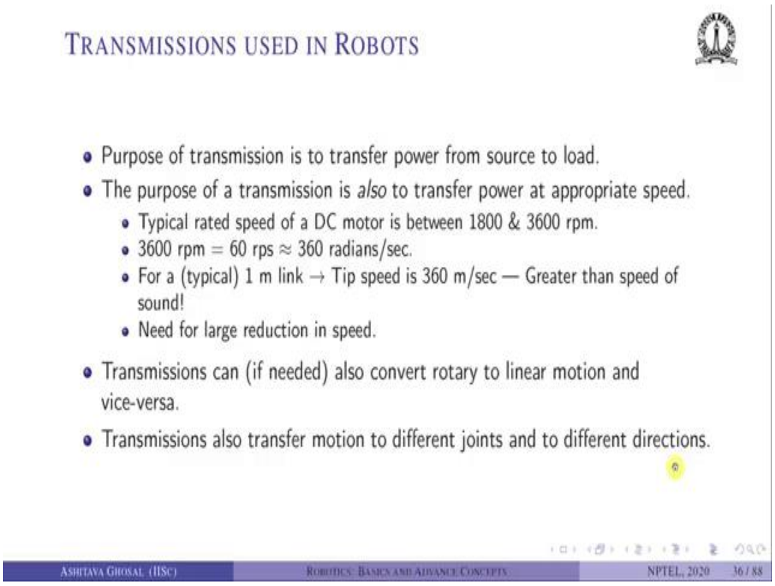

Let us continue. Let us look at transmissions which are used in robots. So, the purpose of a transmission is to transfer power from the source to the load, ok. It is also to transfer power at an appropriate speed, that is important.

Let us take an example. Typical rated speed of a DC motor is between 800 and 3600 rpm, ok. So, for the sake of argument let us our quick calculation, let us assume that the rated speed of a DC motor is 3600 rpm, which is nothing but 60 rotations per second which is roughly equal to 360 radians per second, ok. I am assuming π is 3.

For a typical 1 metre link, if you connect this motor to a 1 metre long link, the tip speed will be $\omega \times$ r, r is 1, so this is 360 radians you will get 360 metres per second. This is really high. It is in fact greater than the speed of sound, ok. So, hence we required a very large speed reduction and that is the reason, one of the purpose of the transmission is to transfer power at the appropriate speed, ok.

What is a typical appropriate speed? Speed, so instead of 60 rps we probably need you know 60 rpm, 1/60th of this. Even then it is like you know 6 m/s which is not a good idea.

We even need smaller, more speed reductions. Transmissions can if needed also convert rotary to linear motion. So, sometimes you have a motor, but I want to implement a prismatic joint, sliding joint, that can be done by using what are called as ball screws; where, the nut of the screw moves up and down when you rotate the inside, ok.

Transmission also transfers motion to different joints and to different directions, ok. So, I can have one motor in one place, and I can using belts and chain and some other kind of transmission. Transfer the motion to some other joint at some faraway place, not very far away at distinct place.

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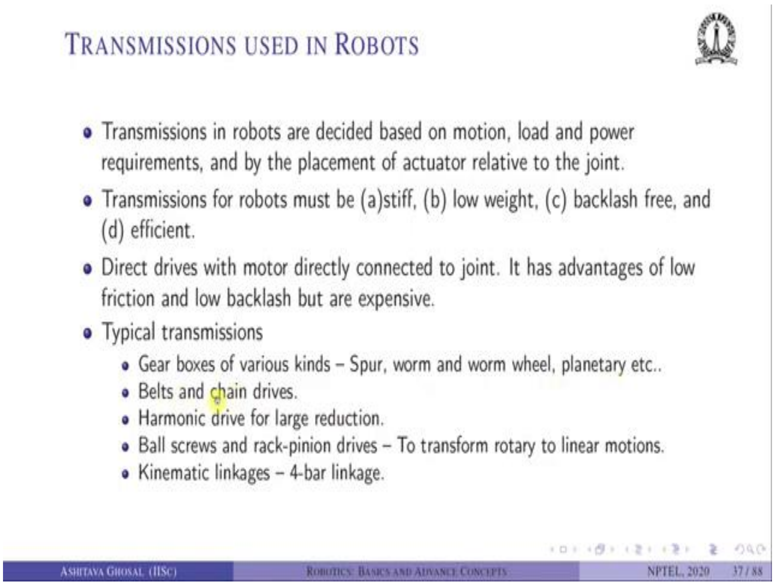

The transmission in robots are use are decided based on the motion, load, and power requirements, and by the placement of the actuators relative to the joint. What are some of the desired properties?

It should be stiff, it should be low weight, it should be backlash free and efficient. Direct drive motors directly connected to the joint are sometimes used, ok. It has the advantage of low friction and low backlash, most of the time whenever you have a transmission you are introducing friction and backlash, but these are very expensive.

Typical transmissions are gear boxes of various kinds spur gears, worm gears, worm wheel, planetary gears. We can also have belt and chain drives. We can have harmonic drives for large speed reductions. We can have balls screw and rack pinion drives to transform rotary to linear motion. And sometimes we also have kinematic linkages. So, we can have a 4 bar linkage to transmit motion from a motor to some (Refer Time: 36:15) jaw for gripper, ok.

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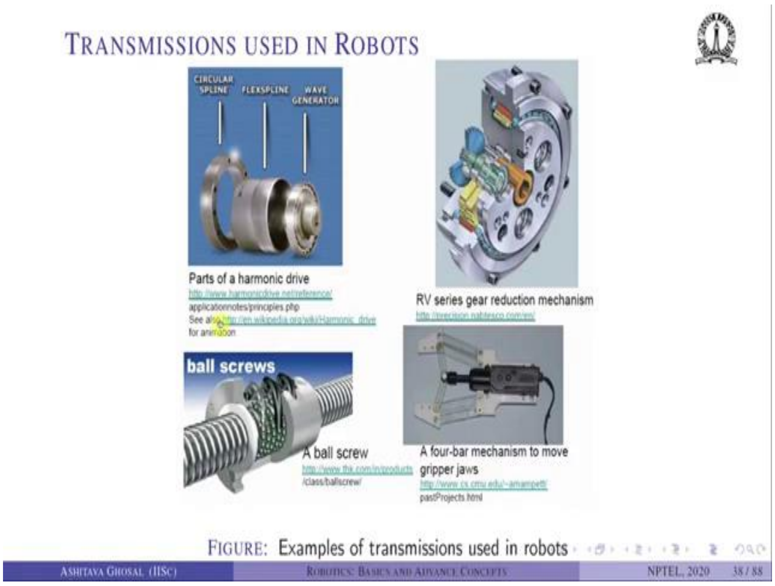

So, this is an example of a harmonic drive. Basically in a harmonic drive we have two flexible members which are called splines, and because of the flexibility you can get very large speed reduction. We can have very sophisticated gear reduction mechanisms, ok. This looks like a cutout view of a gear reduction mechanism with lots of ball bearings and some gears and various other things.

This is a picture of a ball screw. So, basically you have this screw and this is a nut, but it in between the nut and the screw there are these balls. And the advantage of these balls is that it reduces frictions dramatically. And as I said a few minutes back that you can have a 4 bar mechanism to move the jaws of a gripper. So, when I rotate this motor and if you have this 4 bar mechanism, 1 link, 2 link, this and so on.

And if you move this jaws can move parallel to each other which is of advantage, ok. We want to grip an object. We want to jaws to move parallel to each other.

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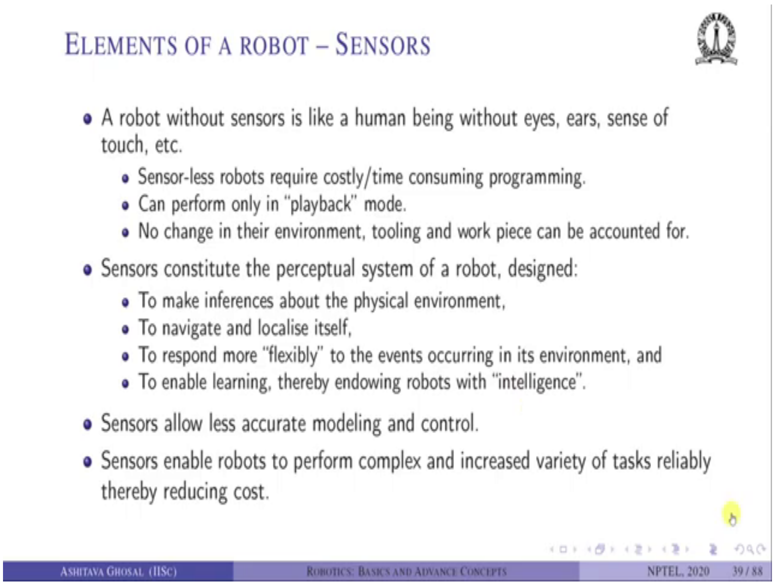

Next we come to elements of a robot which are sensors, ok. A robot without sensors is like a human being without eyes, ears, and sense of touch etc, ok. A sensor less robots requires costly time consuming programming. It can only perform in the playback mode, if you do not have sensors. It cannot adjust to the change in environment tooling and work piece, ok. If the tooling and work piece has changed we cannot account for it in the robot.

Sensor constitute the perceptual system of a robot, ok. They are designed to make inference about the physical environment. They are designed to navigate and localize the robot by itself and they respond more flexibility to events occurring in the environment, ok. So, if somebody comes in front of this mobile robot it will stop, when that person has moved away it can again resume its path. Sensors are designed to enable learning, thereby endowing robots with intelligence.

Sensors allow less accurate modeling and control. We will see later on when we look at control. And sensors enable robots to perform complex and increased variety of tasks reliably thereby introducing reducing cost, ok.

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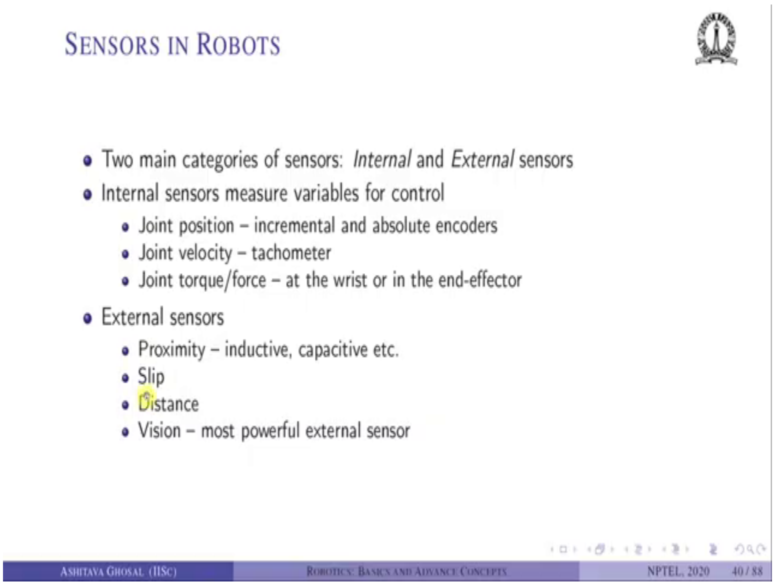

Let us continue. There are two main categories of sensors in robots, these are called as internal and external sensors. The internal sensors measure variables for control, ok. So, we need to measure the joint position. We can use what are called as incremental and absolute encoders. We need to measure the joint velocity; this is measured using something called as a tachometer.

We often need to measure the joint torques and the force with the robot is applying to the environment there is something called the force torque sensor which you can mount at the wrist at the end effector. So, position, velocity, and force are often used to control the robot, to achieve the desired task or to apply the desired force.

We also have sensors which are called as external sensors. These are basically proximity. We want to detect something very close to the robot. We also want to detect slip, so if the robot is gripping some object how do we know that it is gripping properly and that it is not slipping.

We also need to measure distance from of the robot from an obstacle or from some other object which we want to go towards or we want to avoid. And there is this thing called cameras and vision sensor which are very powerful external sensors. A camera can be used for the wide variety of tasks.

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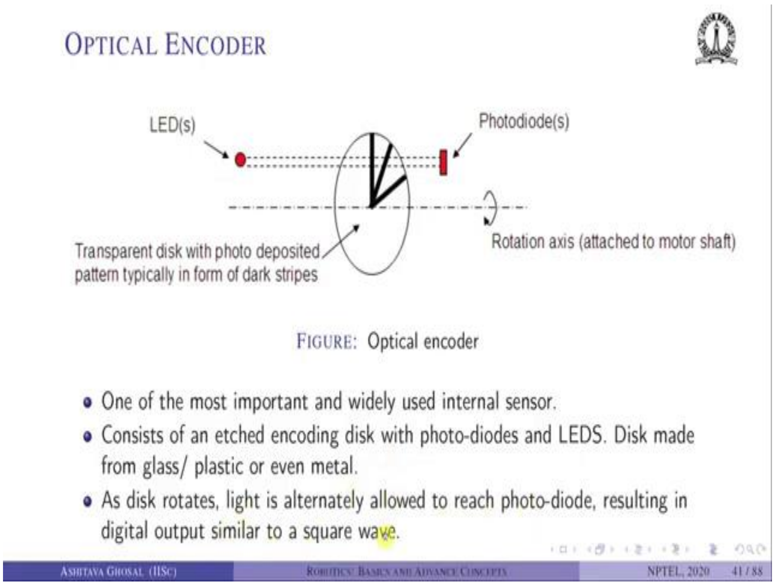

Let us look at optical encoders. An optical encoder consists of the following items. So, basically there is an LED, one or more LED, and then there are this photo diodes. There is a transparent disk and on it we deposit by etching or photo depositing patterns, ok. Most of the time these patterns will be stripes, dark stripes, ok. You can have some other pattern also especially in absolute encoders.

So, now let us connect this disk to the motor shaft. So, when this motor shaft is rotating, the light from the LED will be alternately obstructed by this dark stripes and at the photodiode we will get a signal, ok. So, that is the signal that we measure, ok. So, we count the number of pulses at the photodiode and as you will see little later from that we can find that number of rotation the amount of rotation and even the direction, ok.

So, this is one of the most important and widely use internal sensor, ok. It can measure the rotation of the motor shaft. As I said it consists of an etched encoding disk with photo diodes and LEDs the disk can be made of glass plastic or even metal. As the disk rotates light is alternately allowed to reach the photodiode resulting in a digital output similar to a square wave, ok.

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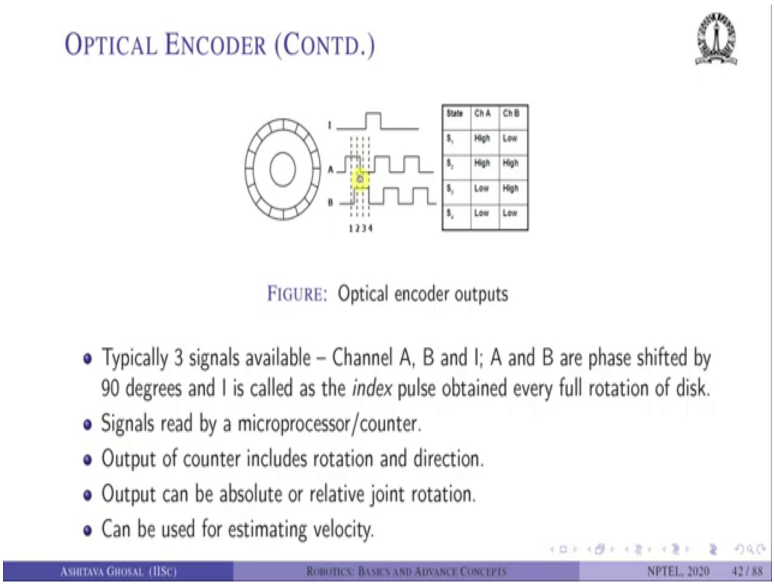

So, this is what it looks like. So, there are typically in has encoded 3 such outputs one is called A. So, you can see one square wave another one is called B which is slightly shifted, A and B are more or less similar, but just shifted by some distance in time. And then there is something called I, this is also called as the index pulse, ok. So, channel A, B, and I are typically available.

A and B are phase shifted by 90 degrees and I is called the index pulse. And this is obtained when the disk completes one full rotation, ok. So, every time you get an index pulse you know that the disk has rotated fully by 360 degrees.

So, as you can see from this A and this signals A and B this pulses are counted in A microprocessor, ok. So, depending on A and B, the number of pulses tells you how much it has rotated. And which one is leading? If A is leading B then it is rotating in one direction and if B is leading A then its rotating in the opposite direction, ok.

So, this is an encoder which is sometimes called incremental encoder. We can also have encoders which measures the absolute rotation, ok. We can also use these signals to estimate velocity. Why? Because if I say that I am getting 20 pulses in let say some time, so what is the estimated speed? It is 20 into something which gives you the amount of rotation divided by Δ_t, ok. So, that will give you the velocity. So, it is very often used to estimate velocity also.

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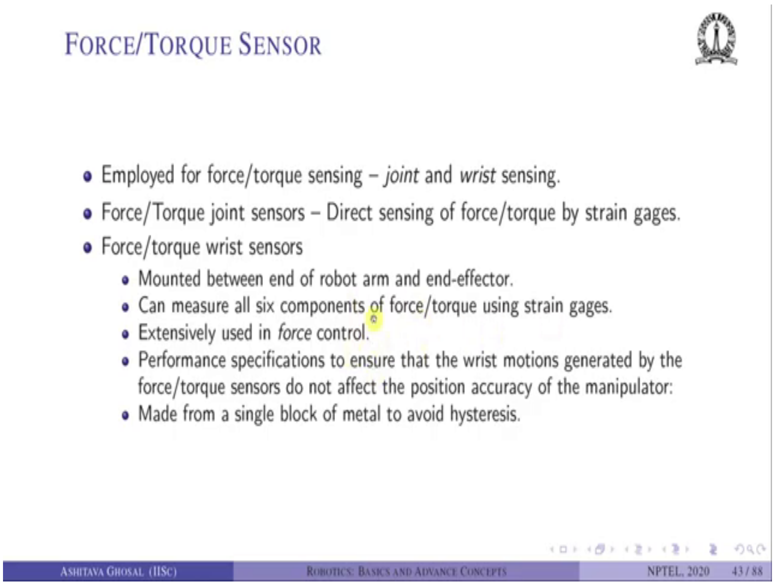

Let us look at a force torque sensor. So, this is sensor is used to measure the forces and moments which are acting at the end effector or at some other points like the wrist, ok. So, we can either measure these forces and torques at the joint and wrist.

So, the force torque joint sensor you can estimate the torque by strain gauges at the joint itself, ok. So, there is a motor, there is a joint, maybe there is a transmission in between and I can set up something with a strain gauge which will tell you how much is the torque which this motor is supplying by measuring some output from the strain gauge.

The force torque wrist sensor is more interesting. It is mounted between the end of the arm and the end effector. And it can measure all 6 components of force and torque using strain gages. It is extensively used in force control. I would like to control the forces which the end effector is applying to the environment, ok. And in any control if you have to measure and use a feedback, so this force torque sensor is used to measure the force and then this feedback control is used to make sure that the desired force or torque is applied, ok.

The performance specification to ensure that the wrist motion generated by the force torque sensor do not affect the position accuracy of the manipulator. This is very important. So, if you are going to mount a force torque sensor at the wrist, it should not affect the kinematics, ok. It should not say because of the force torque sensor some error in tracking is introduced. Most of the time such a force torque sensor which I will showing you next is made from a single metal block to avoid hysteresis, ok.

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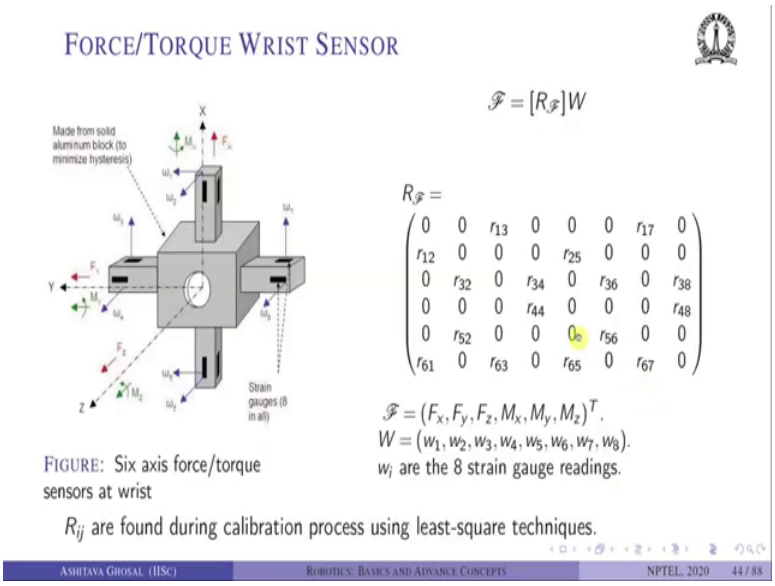

So, how does it look like? So, the force torque wrist sensor consist of a block like, this as this white here is connected to the end effector, and the outside here is connected to the body of the robot or to the other part of the robot. So, basically if you, let us say you are taking some tool here, let us say a wrench or screwdriver which is connected to this white portion and some force and moment which are applied on this wrench.

Because of these members in which we mount some strain gauges these columns or this beams will deflect, because of the force which is applied at this white region. And by measuring the strains we can find what is the force and the torque which this end effector is applying to the rest of the robot body, ok. So, let us do it a little bit more detail.

So, the Z axis as these are shown this way; so, I can apply a Z force and I can also apply a M_z moment. Likewise I can have a F_y force and M_y moment, and M_x moment and an F_x force. We have 8 strain gauges. So, we have w_5 which is on this face, ok, w_6 which is on this face, w_4 here, w_3 here, w_2 in this face w_1 in this face w_7 this way and w_8 this way, ok.

So, if this bending is about the, if there is a torque bending which is about this axis, so there is a force acting here and a force acting here, so the strain gauges w_4 and w_8 will see large outputs, because there is no bending on the other face. Likewise, if the F_z is being applied, then you can see that the second strain gauge, and the 4th strain gauge which is this one, the 8th strain gauge which is this one and the 6th strain gauge which is this one they will see the F_z force, ok.

And likewise for F_x, F_y, M_x and M_y and so on; so, I can find a relationship between the 6 components of force and moment F_x, F_y, F_z, M_x, M_y, M_z which is this variable F. And the strain gauge readings which is there are 8 of them w_1, w_2, w_3, w_4, 5, 6, 7, and 8, and find a relationship between the strain gauge values and the external force, ok.

So, let us just check once. So, suppose I am applying F_x which is in this direction, ok. So, which string gauge we will see the maximum output? It will bend in this direction, right, it will bend like this. So, this w_3 and w_7 we will see maximum output. The others will see very very small output basically due to coupling. So, you will have a non-zero elements r_{13} and a non-zero element r_{17}, ok; likewise all others.

So, suppose let us see what happens when you have M_y. So, M_y is a moment about this Y axis if you have a moment about this Y axis you can see that this w_2 and w_6 outputs will be large. So, we can fill up this matrix with some variables and then these quantities can be obtained using calibration, ok. So, you apply at known force F_x and see what are these values. You change this known force F_x and see the value and due to some kind of a calibration for each one of this R_{ij}'s.

So, once you have calibrated then this R matrix is known, ok. And then if you measure some strain gauge readings you can multiply the strain gauge readings with that R matrix and obtain the F_x, F_y, F_z, M_x, M_y, M_z ok. So, this is the basic idea of a force torque wrist sensor. By measuring these strain gauge readings you can find the external force that the robot is applying.

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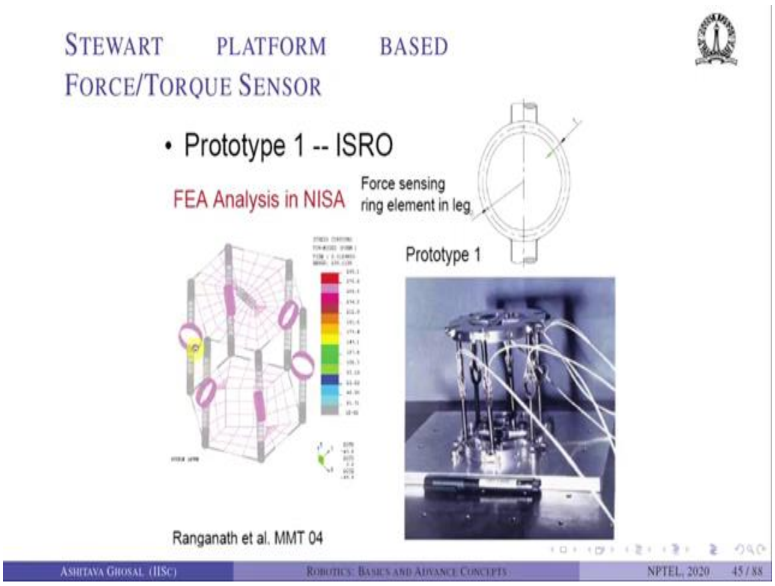

At IISc, we had developed another different kind of force torque sensor this is based on a Stewart platform. So, basically what we have is a Stewart platform which is a top platform here, and there is a fixed platform.

And as I showed you earlier, that there are these legs. So, there is a joint here there is a joint here and instead of that prismatic joint which is sliding in and out sliding joint, we have a ring like this. So, think of it that if I apply a force in this direction this ring will deflect, from a circular it will become more oval, ok.

And if you can somehow measure the strains acting at this in this middle layer of this ring, the middle part will see the maximum strains not here, ok. In a cantilevered beam, if you apply a force at the end of the cantilever the base of the cantilever sees the largest strain and stress.

So, the largest strain will be here. So, we measure the strain gauges at this location here. And for 8, 6 of these we measured all the strains, and we can relate the force and moment which is applied at the top platform to the strains acting on this rings, ok.

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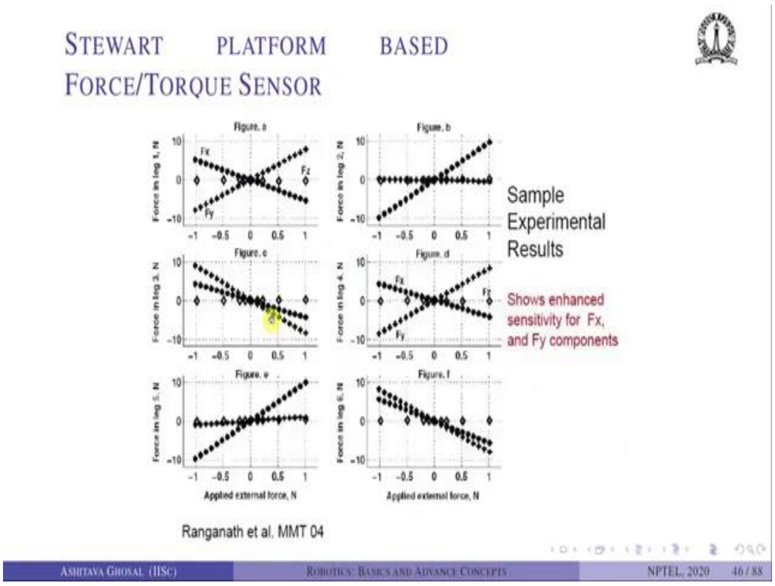

And you can do calibration and although I am not discussing here now. This sensor force torque sensor is designed such that it is more sensitive to F_x, F_y and M_z, ok. We can also design a force stock sensor based on a Stewart platform from for some other components of force and moment. In this one, the legs are more or less vertical, ok. This hexagon at the top and the hexagon at the bottom are exactly equal with such a design you can show that F_x, F_y and M_z will be very very sensitive, sometimes that is required, ok.

In many applications, some forces and moments are very small, but you still need to measure them. So, it is automatically getting amplified in F_x, F_y and M_z direction, ok. So, we did this calibration. So, we apply some known force, ok. So, we will plot F_x, F_y and F_z. So, you can see that the F_z is not changing much, that is F_x and F_y it is changing in the because of in the first leg and so on.

So, these plots show that this sensor is sensitive to F_x and F_y components. These are the plots applied external force and that leg forces that you are measuring. So, in each of these 6 legs, we measured the strengths and from that we can calculate the force.

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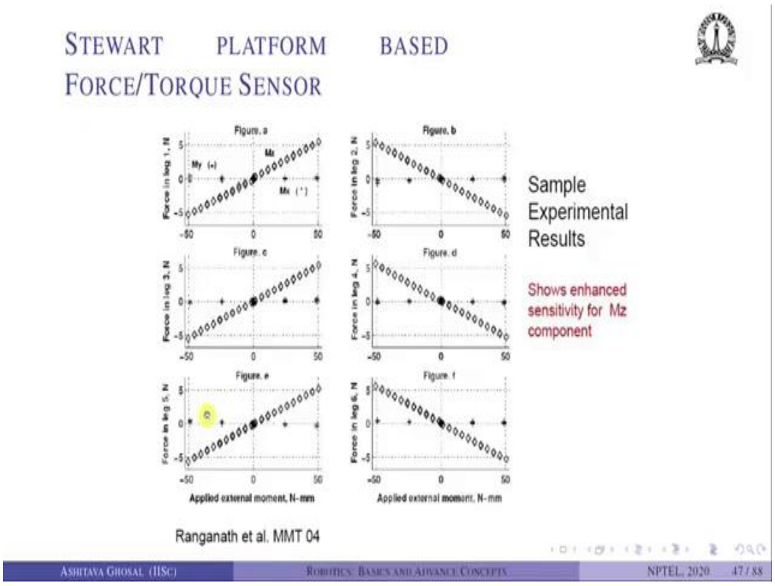

We can also obtain plots for M_x, M_y, M_z, when you apply external moments, ok. So, if we apply some external moment on the top platform, we can measure the strains in the legs and then we can compute the forces which are happening on the leg, and it turns out that M_x and M_y is not very sensitive, whereas the same is very sensitive for M_z. So, when you apply an external moment M_z readings very large, ok.

So, this is a well-designed or a purposefully designed force torque sensor, such that we get very high sensitivity in the F_x, F_y, and M_z directions. We have also built force torque sensor well some other directions have more sensitive.

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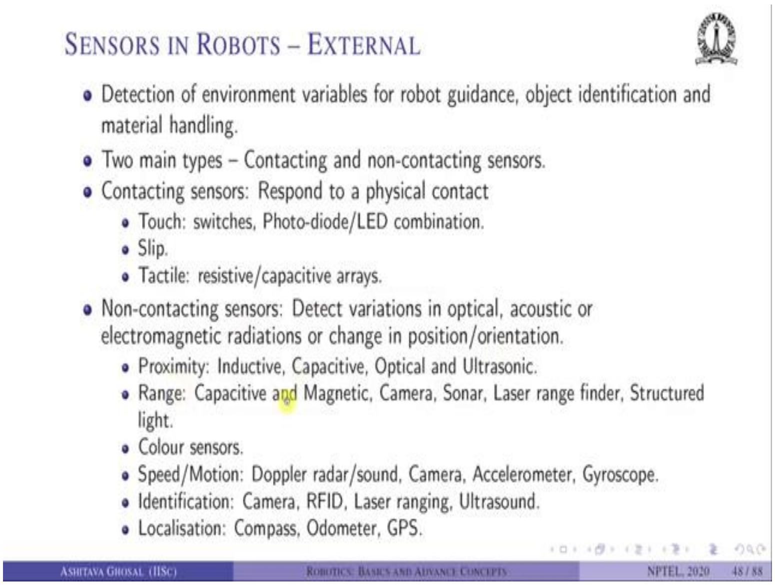

Let us continue. Let us look at sensors in robots which are external, ok. So, what is the purpose of external sensors? To detect environment variables for robot guidance object identification and material handling. So, if I want to see that whether the correct object is there and then they I can command the robot (Refer Time: 55:33) to go and pick it up, if the correct object is not there if I cannot identify the object maybe I do not want the robot to go to that place.

So, there are two main types contacting and non-contacting sensors. The contacting sensors basically respond to physical contact, ok. So, they are touch sensors basically some kind of switches and photo diode LED combination, we can also measure slip and we can also measure touch, ok. Basically, we can have resistive or capacitive arrays and you can feel the environment, ok. We can feel whether it is rounded or some other shape.

Non-contacting sensors detect variation in optical, acoustic or electromagnetic radiations or change in position and orientation, ok. So, we can have proximity. There are various kinds of proximity which are inductive, capacitive, optical, ultrasonic. You have range sensors which can be capacitive and magnetic, it can be a camera, you can also use Sonar, you can use laser range finder, you can also use something called structured light. So, I will show you a few of them.

You can also have color sensors to detect the color of the object. I am not going to discuss this in detail. And then we can measure speed and motion of the object in the environment, ok. So, there is something called Doppler radar, then we can have a camera, we can also have accelerometer, we can have gyroscope. Accelerometer and gyroscope can be used to measure the speed and angular velocity or linear accelerometer and angular accelerometer of the object.

We can also do identification of the object we can again use a camera, there is something called RFID, ok. So, we can have tags on the object and we can read the tags using this radio frequency ID and figure out whether it is the correct object or not. We can have laser ranging and we have ultrasound. Finally, we have localization, I want to know where my robot is in the workspace or in the environment.

So, you can either use compass, we can use odometer, we can (Refer Time: 58:01) if it as a mobile robot, you can count the rotation of the wheel and figure out where how far do you have traveled. You can have GPS, and you can also use camera. So, as you can see camera is very very useful. It can be used in many such applications.

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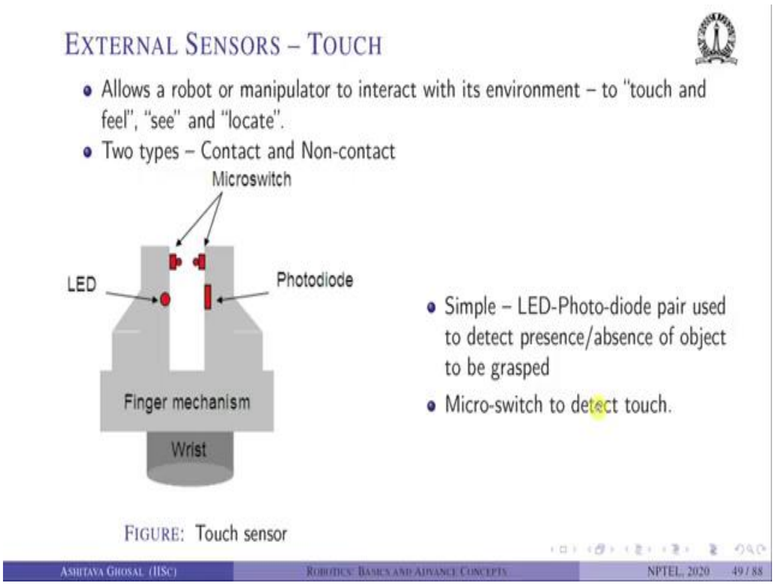

Quickly go through some of these common sensors. So, if you want a touch sensor, so basically what do we have? We have a micro switch and a LED and photodiode, ok. So, this sensors allows you to touch, feel, see and locate the object. So, if there is an object in this finger mechanism and if it touches you will get a signal from this micro switches. You can also see that this light beam will be blocked and you know whether the object is inside the fingers or not, ok. There is a simple LED photodiode pair used to detect presence, absence of object to be grasped.

So, I would like to know whether the object is there before I would command the robot of that gripper to grasp it, ok. When do you stop? When the micro switch detects, that it has touched.

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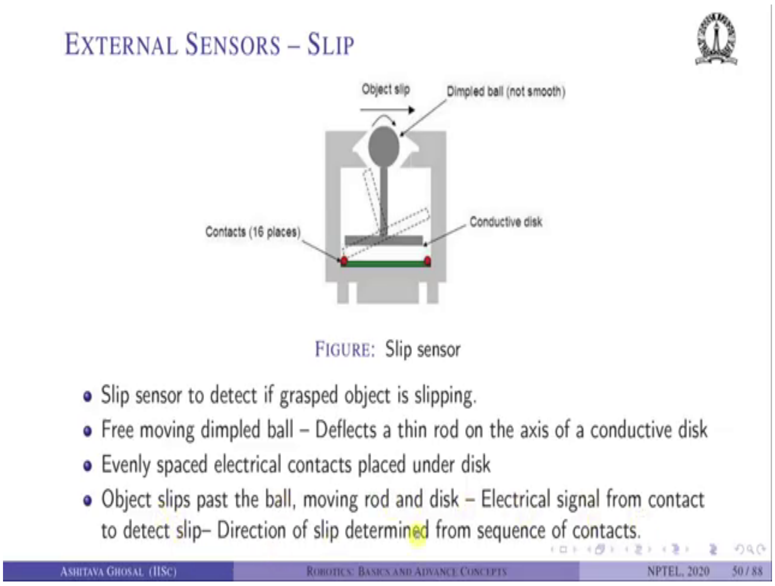

You can also have external sensors which are also to measure slip. So, basically it is again like a gripper, but inside the gripper that are like a object here there is a dimpled ball, ok. So, the actual object is here. And in this dimpled ball it is connected to a disk which can rotate.

So, when the ball rotates this disk below can touch some contact points here, ok. So, if the object is slipping in this direction then the contacts will be here, ok. And if it is slipping in some other direction you have some other contact. So, a slip sensor is basically used to detect if the grasp object is slipping.

It is a free moving dimpled ball. It deflects a thin rod on the axis of the conducting disk. Evenly spaced electrical contacts placed under the disk. This is a schematic. It is much more compact. If the object slip past the ball, the moving rod and disk, electrical signals from the contact to detect slip ore obtained, ok. And the direction of slip is determined from the sequence of contacts here.

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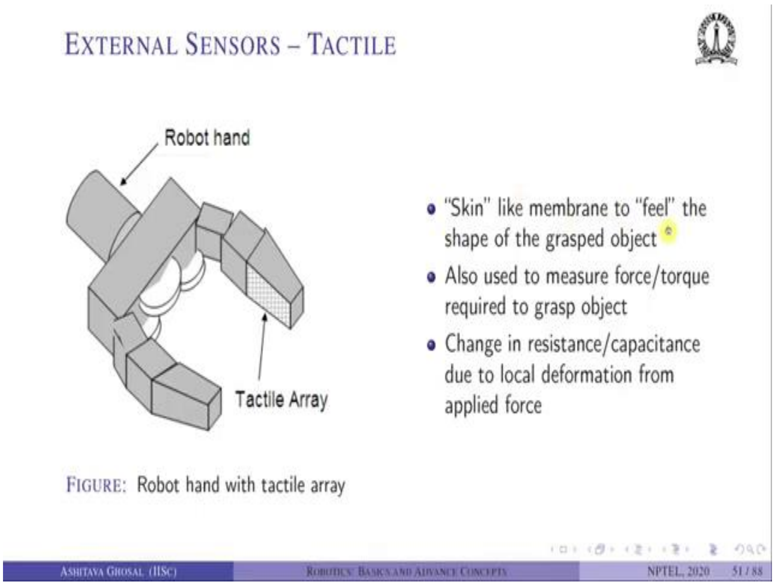

You can also have what are called a tactile arrays. So, (Refer Time: 60:45), ok. So, it is a skin like membrane to feel the shape of the grasped object, ok. You can also use to measure force torque required to grasp the object. And basically, as I will show in the next slide, there is a change in resistance or capacitance when you apply a pressure on an object, and that change in resistance of capacitance is used to feel that shape of the object, ok.

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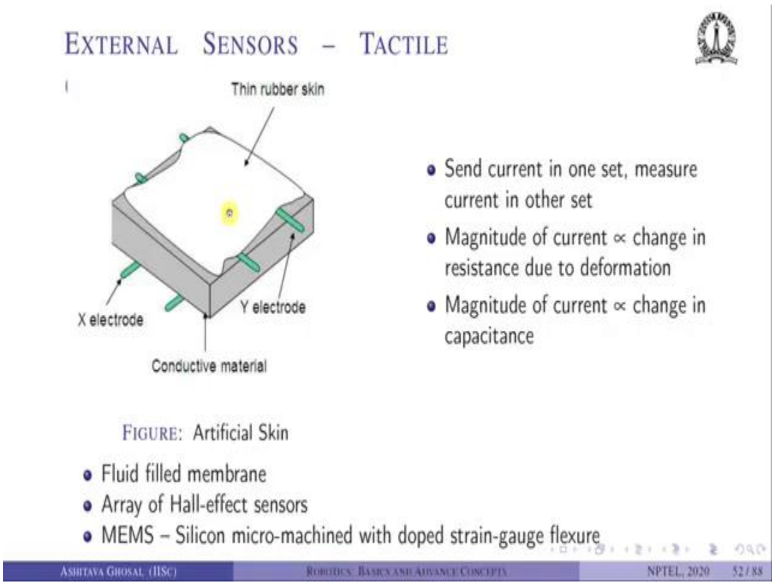

So, typically a tactile sensor consists of a thin rubber skin. There is a set of electrodes which we will call X electrodes and another set of electrodes which are perpendicular to this called the Y electrodes. So, we send current through one set of electrodes and we measure in the other set.

So, basically what happens is the magnitude of the current is proportional to the change in resistance due to the deformation of this piece of this conducting material. So, if there is an object which is sitting here and you are gripping it, some points between the X and Y electrode will be shorter than the other points.

So, the resistance between say this point and this point is different than resistance between this point and some other point below, ok. So, and that is seen by the change in the current when you scan this the Y electrodes, the current is going through the X electrode and you scan the Y electrode. So, in some places the currents will be smaller, ok.

It also you can sense the change in capacitance. So, if this material changes capacitance when you compress it we can also use that. So, these are sometimes called as artificial skins, ok. There are lots of attempts for artificial skins using other physics. So, we can have a fluid filled member here, membrane, and when you press the fluid will change the shape of the membrane will change, and from that you can find out the shape of the object.

You can also have what are called as Hall effects sensors, ok. And we can have an array of this Hall-effects sensors which also tells you where there is contact or where there is pressure. We can also have MEMS, sensors basically these a silicon pieces which are micro machined and doped with strain gauge flexure, ok.

So, it is like basically lot such strain-gauges and when you use this sensor it can tell you where the strains are different. And the strains are different wherever there is pressing or wherever there is deformation, ok. And wherever there is deformation if you have several such points you can get an idea of that shape of the object. So, these tactile sensors allow you to touch, feel, and sense the shape of the object that you have grasped.

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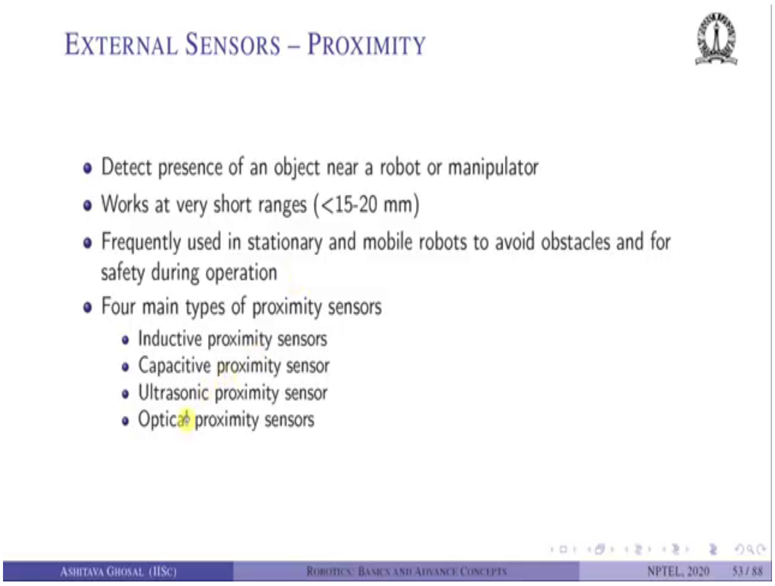

We can also have external sensors which detect the proximity, ok. So, it detects basically the presence or absence of an object near to the robot which is not for large distances. So, it works for very short, ranges between let us say 15 to 20 millimeters.

It is frequently used in stationary and mobile robots to avoid obstacles and for safety during operation, ok. There are four main kinds of proximity sensors you can have inductive, capacitive, ultrasonic, and optical. So, I will show you a few of them how they work.

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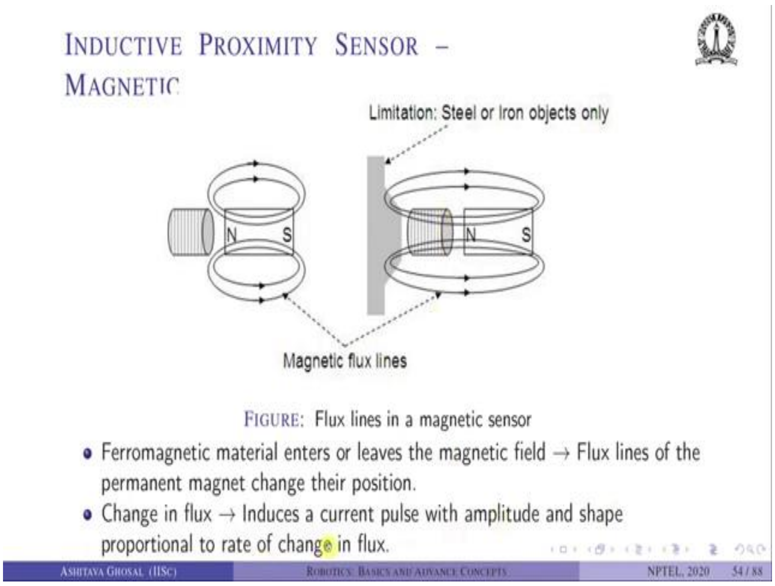

So, the inductive proximity sensor basically consists of a coil and a magnet. So, if you bring this object closer to a steel or an iron or a ferromagnetic object, the field lines will change and you can sense the change of the field lines in this coil.

So, for example, it could be like this the coil is seeing nothing and when you bring something you can see some intersection of the coil with the field lines, ok. So, the change in flux introduces a current pulse with amplitude and shape proportional to the rate of change in flux, ok.

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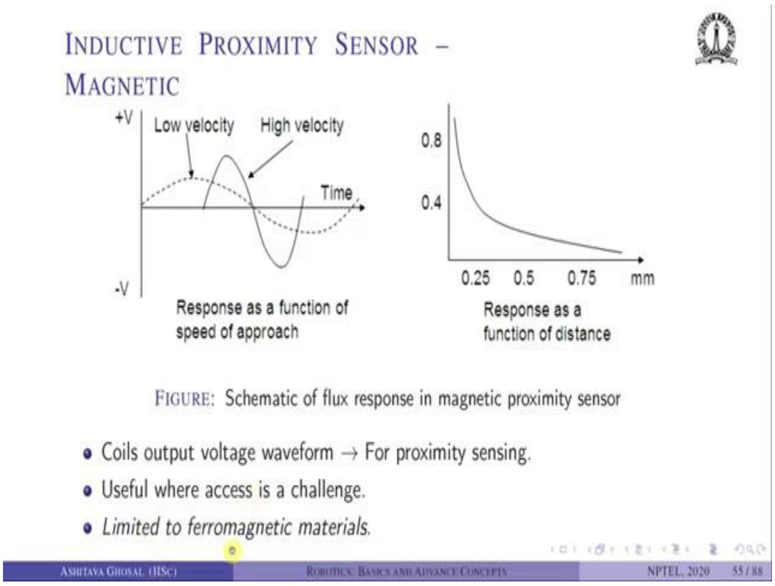

So, we can get an output which looks like this when you bring this magnetic inductive sensor closer to a ferromagnetic object. So, if you bring it slowly the voltages will be lower than if you bring it at high speed, ok. Typical response is that it works only if very close by, ok. So, if you have some plot if you go far away from the object the output is very low. So, this is very useful where access is a challenge.

I cannot go to an object very close to each other. So, if I can take this probe and come close to it, I can detect whether there is a metal and object there or not, ok. Unfortunately, it is limited to ferromagnetic materials.

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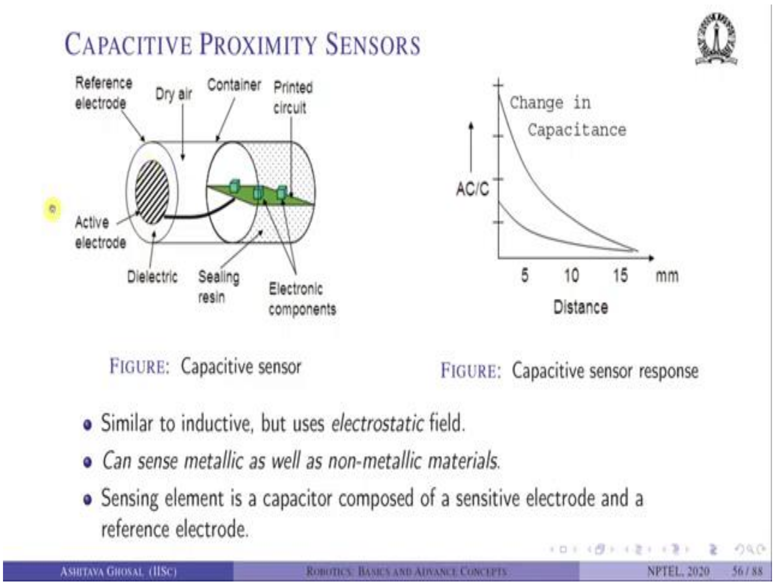

You can have capacitive proximity sensors. So, basically it consists of an reference electrode, and an active electrode in between we have air and then we have sealed and then we have some circuits inside. So, basically if you bring this electrode which for which there is a voltage which is applied and you bring it near an object that equivalent capacitance between this electrode and the outside will change, ok. So, the change in capacitance can be sensed with distance.

So, if it is like far away like 15 or 20 millimeters away, then the change in capacitance will be very small. But if you bring these active electrodes very close to an object the change in capacitance will be much larger, ok. So, it is very similar to this magnetic inductive idea, except it is using electrostatics.

It can sense metallic as well as non-metallic objects, ok. As I said there is a reference electrode with some voltage. There is an active electrode, there is an electrostatic. So, some capacitance is there, when you bring it closer to an object the capacitance changes and you will get a different voltage, ok.

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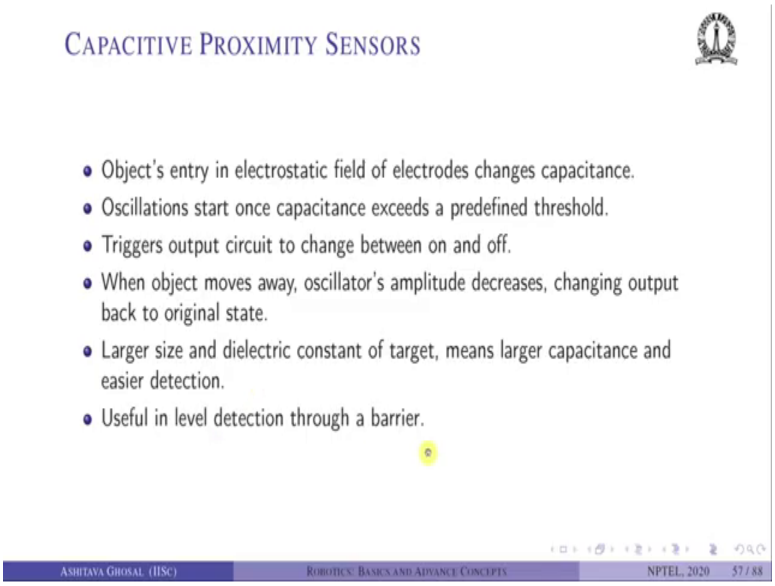

So, as I said the objects entry in the electrostatic field of electorate changes capacitance, ok. Oscillations will start once the capacitance exceeds a predefined threshold. You can have an RC circuit there. So, this triggers output to change between on and off, ok. So, you can sense and you can set the value of these oscillations.

If it is below some amount there is no object. If it is above some amount it is close to the object. When the object moves away, the oscillator's amplitude decreases again because change in capacitance is smaller and then we can change it back to the original state, ok. If you have large size and dielectric constant of the target, it means larger capacitance and easier detection, ok.

So, there is something called dielectric constant which modifies how much the capacitance is changing, if the size of the object is larger than the change in capacitance is also larger. And it is very useful to detect level through a barrier, ok. Because you cannot go to the object because there is a barrier, but you can take this capacity of proximity sensor and find out what is the level or where the object is.

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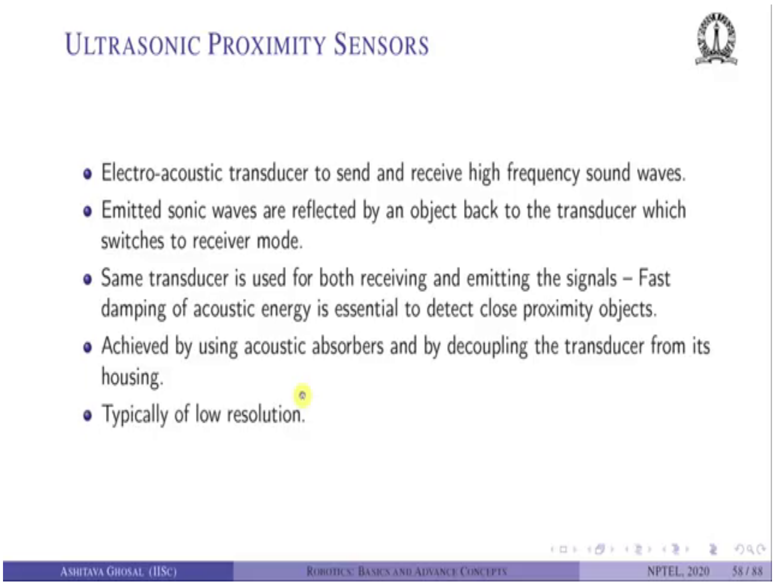

We can also have ultrasonic proximity sensors. Basically, these are electro-acoustic transducers; we send and receive high frequency sound waves. The emitted sound waves are reflected by an object back to the transducer which switches to the receiver mode, ok. The same transducer is used for both receiving an emitting signal, ok.

Fast damping of acoustic energy is essentially to detect close proximity of objects. And basically achieve by using acoustic absorbers and by decoupling the transducers from its housing. This is typically a very low resolution.

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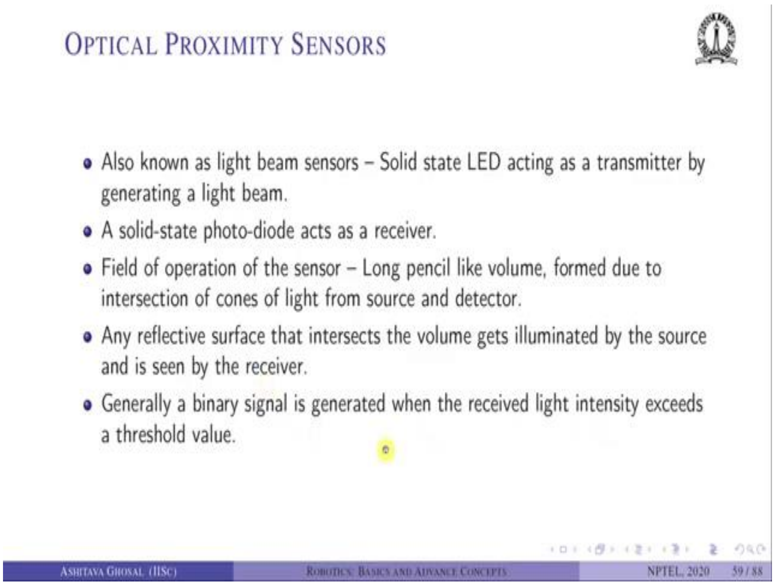

We can also have optical proximity sensors. This, these are called light beam sensors. We have a solid state LED acting as a transmitter by generating a light beam, ok. A solid-state photo diode acts as a receiver. The field of operation of the sensor is this long pencil like volume formed due to the intersection of cones of light from a source and a detector.

Any reflective surface that intersects the volume gets illuminated by the source and is seen by a receiver. Generally a binary signal is generated when the received light intensity exceeds a threshold value. So, we can see whether there is an objective point of view or not.

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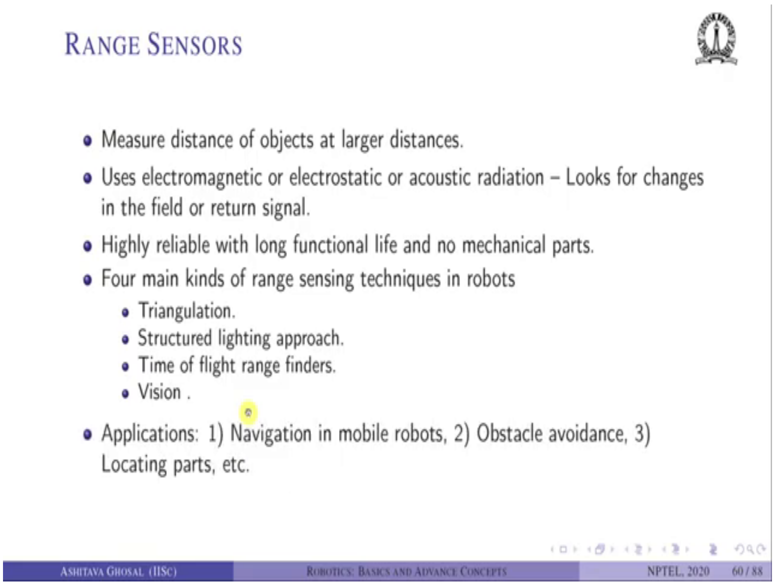

We can also have range sensors. Range sensors are typically used to measure longer distances. Not close to the robot, but objects that are much larger distance. We can use electromagnetic or electrostatic or acoustic radiation, ok. So, it looks for changes in the field or the return signal. These are highly reliable with long functional life and no mechanical parts.

There are four main types of the range sensing which are used in robotics. One is called triangulation. One is called structured lighting approach. Then you can sense the difference in the time of sending and receiving the signal these are called time of flight range finders. And then you can have camera, a vision, ok. The main application of range sensors are in navigation in mobile robots, obstacle avoidance, locating parts, etcetera.

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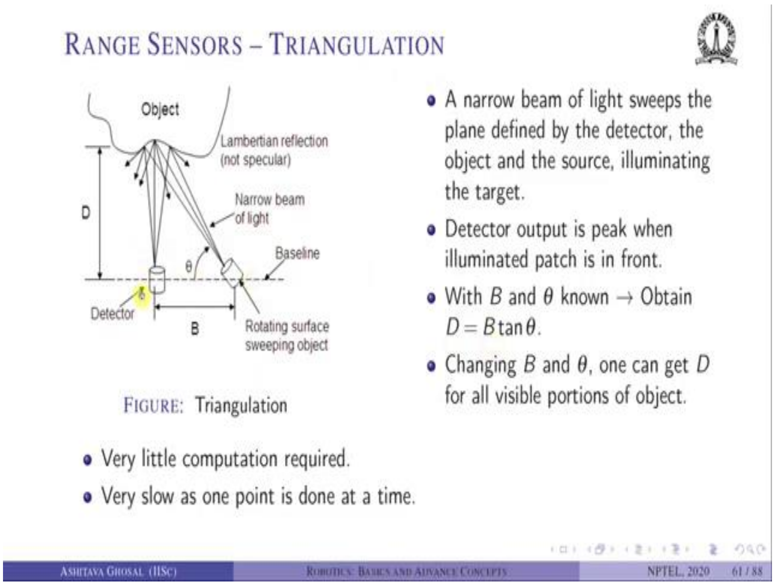

So, let us look at triangulation. So, basically we have emitter, ok. So, it is sending out narrow beam of light. Suppose, there is an object and you can scan or rotate this emitter and there is a detector which is at the distance D, this B is not. So, when you are rotating, when this object is directly in front of you will get a large signal, ok. So, the detector output is peak when the illuminated batch is in front.

So, if B and θ are known at that instant we can get D as

$$D = B \tan \theta$$

So, if you change B and θ one can get the object the distance of the object at different points. But it must be visible to this light source. There is almost no computation required. This is very very simple.

All we need to do is know what is B and then find when you get the peak detection at and the angle at which the peak detection is happening and when we quickly know what is D which is just we need to do tan of that angle. It is very slow because we have to do one point at a time, ok. So, as you can see if you send this beam, most of the time it is scattered.

If it were the mirror this will not work, this idea will not work. So, those are called specular reflection. This object or this technique will work if the object is showing Lambertian reflection, basically it is scattering. If it was specular, then the i equals r you will not see anything at the detector.

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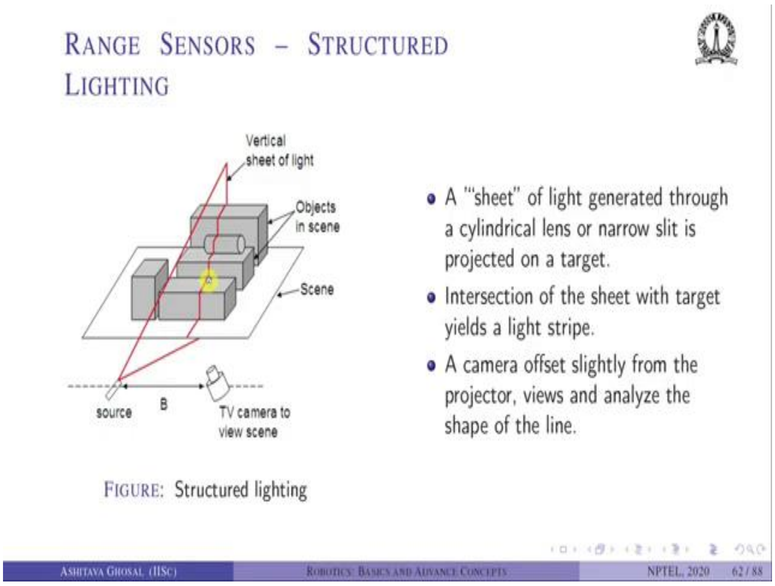

The next well-known way of detecting range or measuring range is something called structured light. So, let us look at what it involves. So, we have a source of light, but this source of light is now generating a sheet of light, not a single beam, ok. And let us assume there are these objects in the scene. So, how do we generate a sheet of light? We can generate a sheet of light through a cylindrical lense or a narrow slit, like a projector.

So, when this sheet of light intersects an object, and if you are looking at the scene from a camera at a slight angle you will see these lines, you will see one line, one more line, then there is a gap one more line and there is a curve and so on, ok. So, the camera which is offset slightly from the projector views and analyzes the shape of these lines, ok.

And by using some kind of calibration and by knowing what the shape of the line is, we can find out that this object is nearer to than this object and we can even get a sense of distance by calibration, ok.

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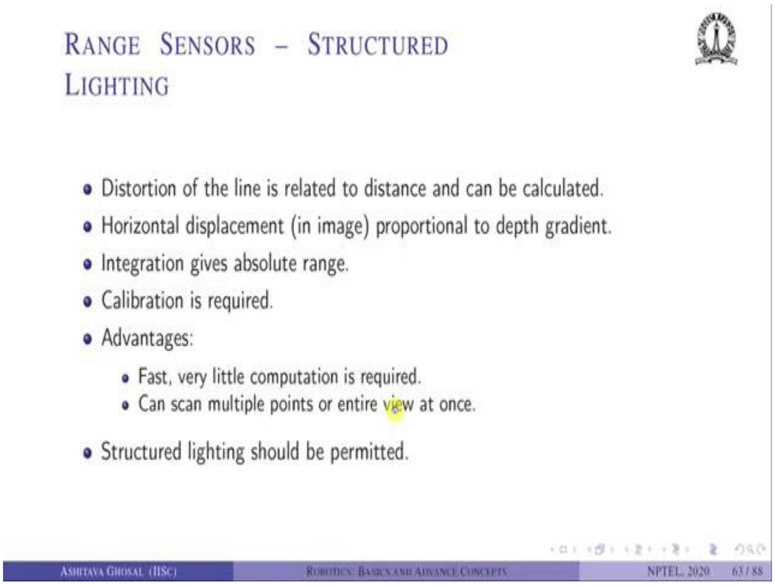

So, the distortion of the line is related to the distance and can be calculated. The horizontal displacement in the range is proportional to the depth gradient is to give some more information.

And integration gives absolute range and we need to calibrate to obtain the distance, the range. It is very fast advantage, very little computation is required and can scan multiple points or entire views at once, ok. The big thing is you should be allowed to sign a sheet of light in the scene, otherwise this whole thing does not work.

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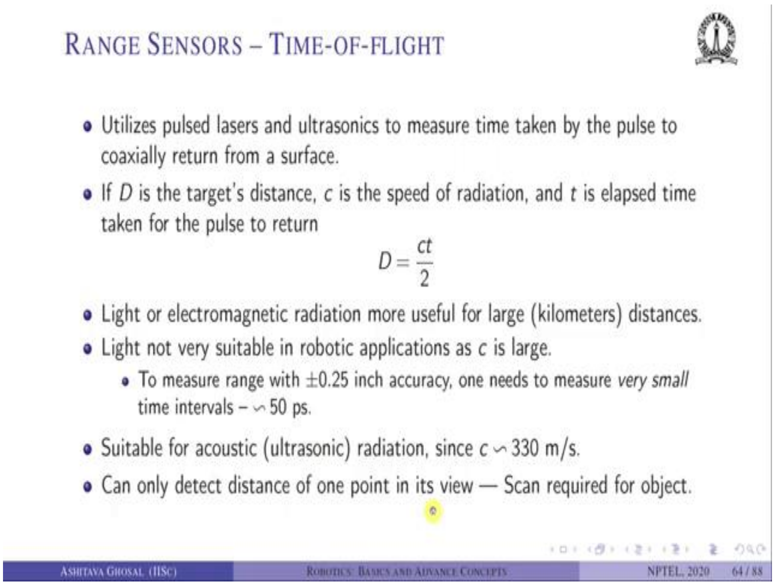

The time of flight sensor works basically with the idea that you send the pulsed signal either from a laser or an ultrasonic device, you find the time taken by the pulse to return from a surface from where it is reflecting, ok. So, if D is the target distance, c is the speed of radiation and t is the elapsed time, then

$$D = \frac{ct}{2}$$

So, for light this is not very useful because c is very large, you know it's 3×10^8 meters per second, ok. But it can be used for measuring large distances because if it is very close this elapsed time will be very very small, ok. So, if you want to, as an example if you want to measure a range with this ± 0.25 inch, we need to measure time intervals of the order of 50 picoseconds which is not very easy to do.

However, this idea can be used for acoustic or ultrasonic radiation, ok. Why? Because this c is the much smaller it is 330 meters per second as opposed to 3×10^8 meters per second, ok. This time of flight sensors can only detect distance at one point in its view from wherever the reflection is happening. And if you want to find different distances, we have to scan the object.

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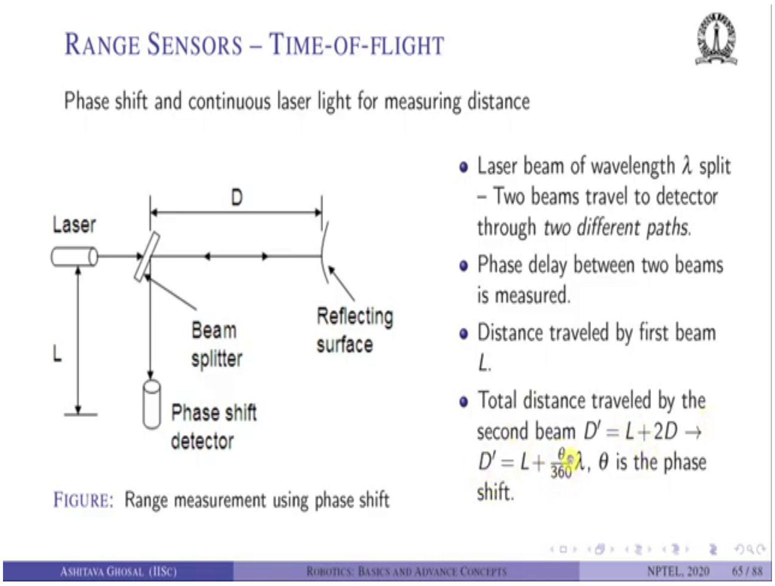

Another way of using the time of flight is by modulation, ok. So, the idea is the following. Instead of measuring the time of flight we will measure the phase shift of the beam. So, we have a laser beam and then at some L of the detector, then we split the beam in two ways, one directly goes to the phase shift detector and one goes to the object and gets reflected, ok.

So, the phase delay between the two beams is measured. So, the distance traveled by the first beam is basically L, the distance travel by the second beam is D′ which is L + 2D, and $D' = L + \frac{\theta}{360}\lambda$ were θ is the phase shift, ok.

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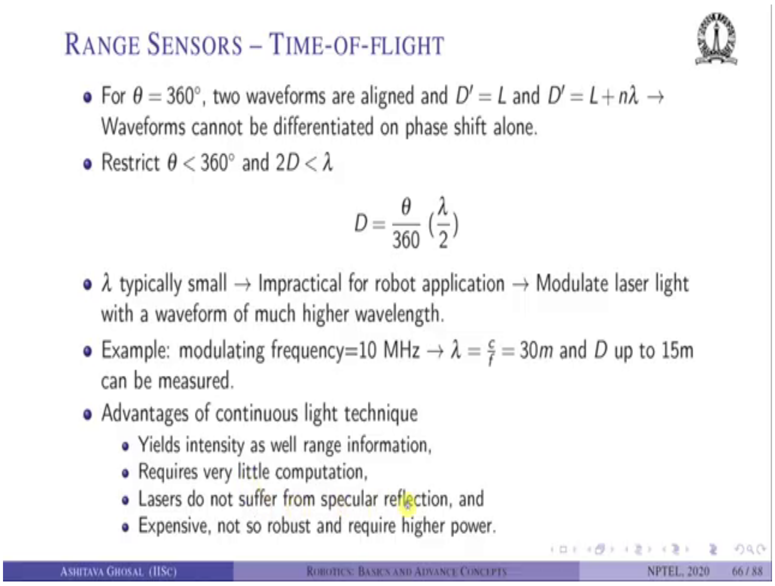

So, if you can measure the phase shift, so for $\theta = 360$ the two wave forms are aligned and $D' = L$ and $D' = L + n\lambda$, ok. The waveforms cannot be differentiated on phase shift alone. If you restrict θ to less than 360 and 2D to be less than λ, so then this distance is directly related to the phase shift θ and in fact, the expression is $\frac{\theta}{360}\frac{\lambda}{2}$. So, I mean know the wave length, I can measure the phase shift and I can find the distance, ok.

So, typically λ is very small. It is impractical again for robot applications, ok. So, λ of light is a very very small, is of the order some microns. But we can modulate this laser light this is what I meant, ok. So, we can modulate that beam with a waveform of much higher wavelength. So, for example, if the modulating frequency is 10 MHz then this $\lambda = \frac{c}{f}$ is 30 meters, and distance up to 15 meters can be now measured, ok.

The advantages of this continuous light technique is it yields intensity as well as range information, it requires very little computation and lasers do not suffer from specular reflection, and it is expensive and not so robust, it requires much higher power.

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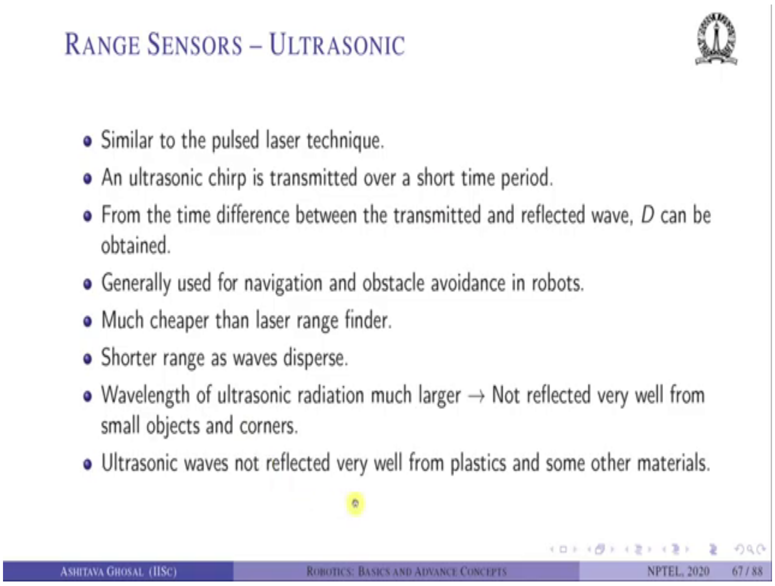

The range sensor which are ultrasonic are very similar to pulsed laser, instead of a light pulse we generate a ultrasonic chirp, which is transmitted over a short time period. From the time difference between the transmitted and the reflected wave, D can be obtained.

And it is generally used for navigation and obstacle avoidance in robots, ok. You remember the speed is much smaller, so we can find out distances closer. It is much cheaper than laser range finder, ok. Shorter range is more desirable. If you want to measure large distances this ultrasonic waves of disperse and you will not get a very good signal, ok.

The wavelength of the ultrasonic radiation is much larger. Unfortunately, it is not reflects from very well from small objects and corners. So, I cannot use these ultrasonic range sensors if the object is very small. The ultrasonic waves are also not reflected very well from plastics and some other materials. So, if you have lots of plastic in your environment and if you have ultrasonic range sensor it will give sometimes harmonious results.

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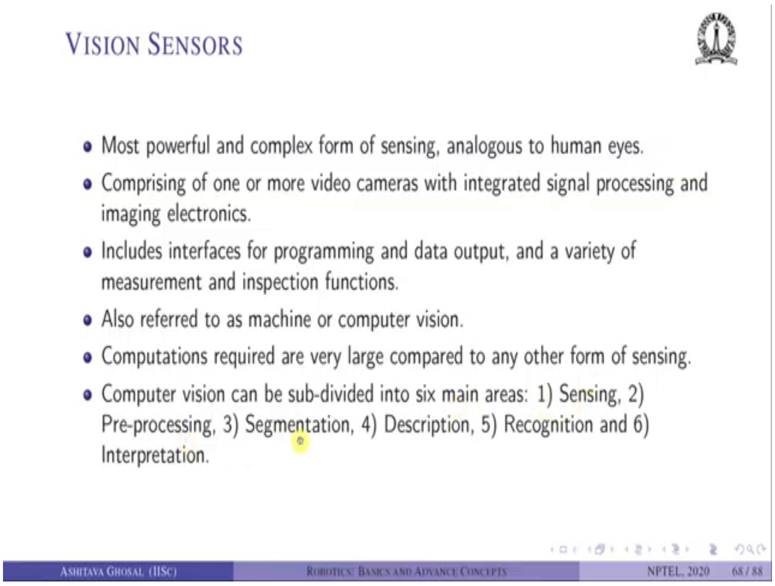

Finally, we have vision sensor, ok. As I have mentioned earlier, it is one of the most powerful and complex form of sensing it is analogous to human eyes, ok. It comprises of one more video cameras with integrated signal processing and imaging electronics.

It includes interfaces for programming and data output, and a variety of measurement and inspection functions, ok. This technique is also sometimes referred to as machine or computer vision, ok. There is a whole field called computer vision there lots of work and lots of research and lots of papers in this area of machine vision and computer vision, ok.

A large amount of work is done in computer vision simply because the computations required are very large, compared to any other form of sensing. So, instead of proximity or laser range finder or any of these techniques, cameras require a huge amount of computation and only very recently we can have processors which can process the measurement by a camera and obtain good estimates of distance.

Computer vision can be subdivided into 6 main areas, first is sensing, two is pre-processing, third is segmentation, this is an important part in computer vision. This takes quite a bit of time, ok. I need to know where there is shade and where there is image, where the reflection is, ok. We need to know the edges that is what is called segmentation. Then, you can find some description, then you need to recognize the object and then you need to interpret. So, each of these requires a huge amount of or significantly large amount of computing.

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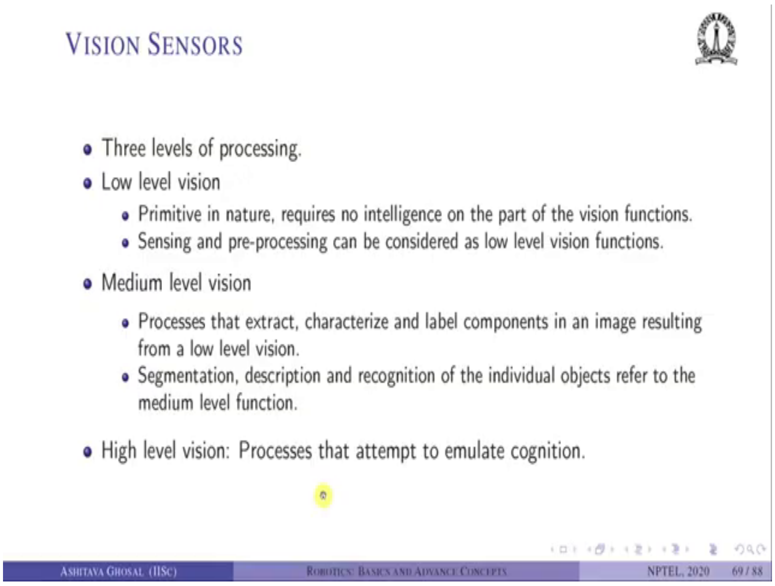

There are three levels of processing. We have low level vision which are primitive in nature, requires no intelligence on the part of the vision functions. Sensing and pre-processing can be considered as low level vision functions, ok. Medium level vision we extract, characteristics and label components in an image resulting from low level vision. This is the second stage. It requires segmentation description and recognition of the individual objects at this stage, ok.

So, is it the cube or is it the sphere we need to recognize, ok. So, these are some of the medium level vision functions. And the high level vision function is basically we want to emulate cognition, ok. Looking at the scene once we know it is some object can we infer something or can be taken action based on that. So, that is what is cognition, ok.

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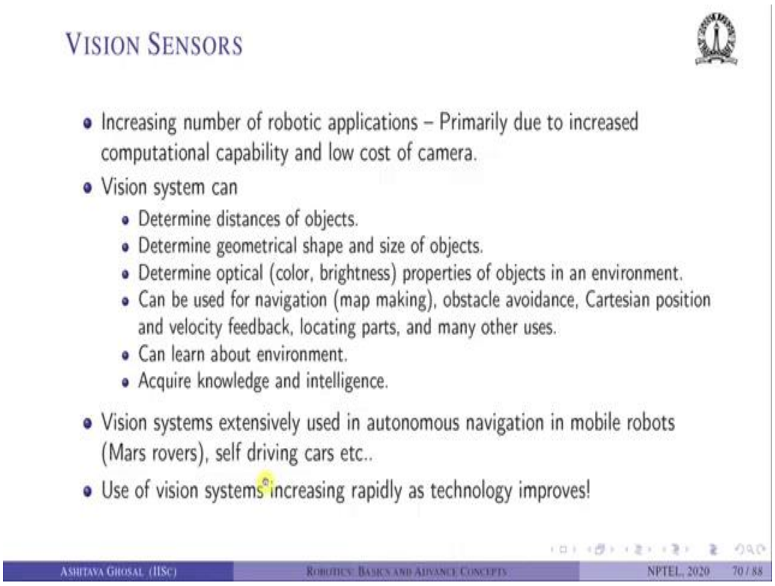

There are increasing number of robotic applications using vision sensors. This is primarily due to the increase in computational capacity and low cost of camera. So, there are now cameras which are very cheap, and which can be used for computer vision. The vision system can determine the distance of objects. It can determine the geometrical shape and size of objects.

It can also determine color, brightness properties of objects, it can be used for navigation, it can be used to make a map, it can be used to do obstacle avoidance, it can even be done for Cartesian position and velocity feedback, ok. So, if I know the distance, I can somehow obtain the estimator velocity also. It can we used to parts and many many other usage, ok. A vision system can also learn about the environment there is a lot of research going on to automatically do this medium level segmentation and trying to figure out what object it is.

It can also be used to acquire knowledge and intelligence, ok. Vision systems are extensively used in autonomous navigation in mobile robots, Mars rovers is the simple example. You know the robot is moving around in Mars. There is a time delay between the signal coming from Mars to JPL or wherever it is controlled from, ok. In between, it must do something autonomously because it cannot wait for instructions always from earth, ok. So, that is what is called autonomous navigation.

So, a camera is there which you will see whether there is a ditch in front or not while it is moving. If there is a ditch it can take some decisions and stop or it can go around. It is also seen in self-driving cars. Nowadays there are many self-driving cars which are coming up and they had vision cameras which can sense whether there is a person in a spot or not, or whether there is another car in front or not, or I can even sense whether there is a green light or a red light at a traffic intersection.

So, the use of vision system is increasing rapidly and as the technology improves it is expected to become more and more mature. There will be many more uses of computer vision in vision technology.

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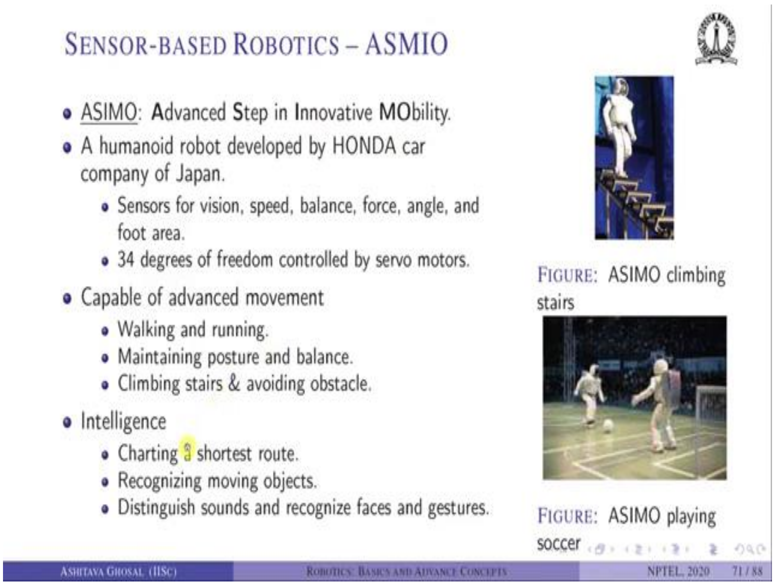

I will end this part on sensing with one example of a sensor base robot, a very well-known example. This is called ASIMO, ok. ASIMO stands for Advanced Step in Innovative Mobility. So, basically this is the humanoid robot developed by HONDA car company. You know it is very far from their normal line of business of making good cars, ok.

So, this robot which is shown here it looks like a humanoid. It has legs, it has arm, it has a head in which there are lots of sensors. There are sensors of vision, speed, balance, force, angle, and foot area. It has 34 degrees of freedom controlled by servo-motors, ok. There are 34 joints in this robot that they are all controlled by servo-motors.

This robot can is capable of walking and running. It can maintain posture and balance. It can climb stairs and avoid obstacles. So, in this example you can see that it is trying to play soccer. In this example it is climbing stairs, ok. In this example of clamping down, but it can climb up also. It is capable of having some intelligence. Basically, what is the level of intelligence it has?

It can chart a shortest route from point a to point b using the camera. It can recognize moving objects and take decisions. It can distinguish sounds and recognize faces and gestures. So, if it is talking it can turn towards you, if you are talking and then it can shake hands. So, there are these examples of this robot checking hands with very distinguished people, on its own. So, this is the one of the best example of sensor based robotics.

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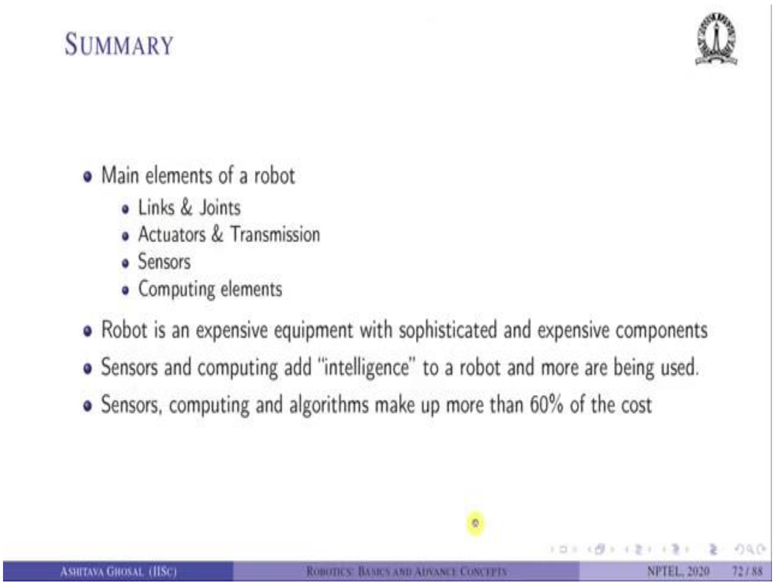

So, in summary the main elements of a robot are links and joints, actuators and transmission, sensors and computing elements. The robot is the very expensive equipment and sophisticated, and with expensive components. Sensors and computing add intelligence to the robot and more of sensors and computing are been employed in robots.

Sensors, computing and algorithms make up more than 60 percent of the cost, ok. So, you might think that the motors are very expensive that is not true, the sensors computing and algorithms which go into making a robot intelligent and autonomous or almost 60 percent or more of the cost, ok.

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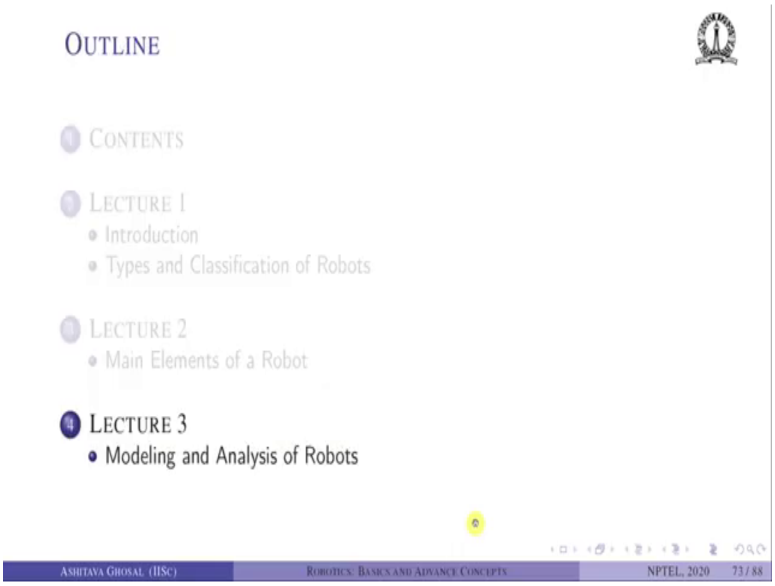

So, with this I will stop this lecture. We looked at the main elements of a robot. In the next lecture, we will look at some of the modeling and analysis techniques used in robots.