NPTEL Online Certification Courses
COLLABORATIVE ROBOTS (COBOTS): THEORY AND PRACTICE
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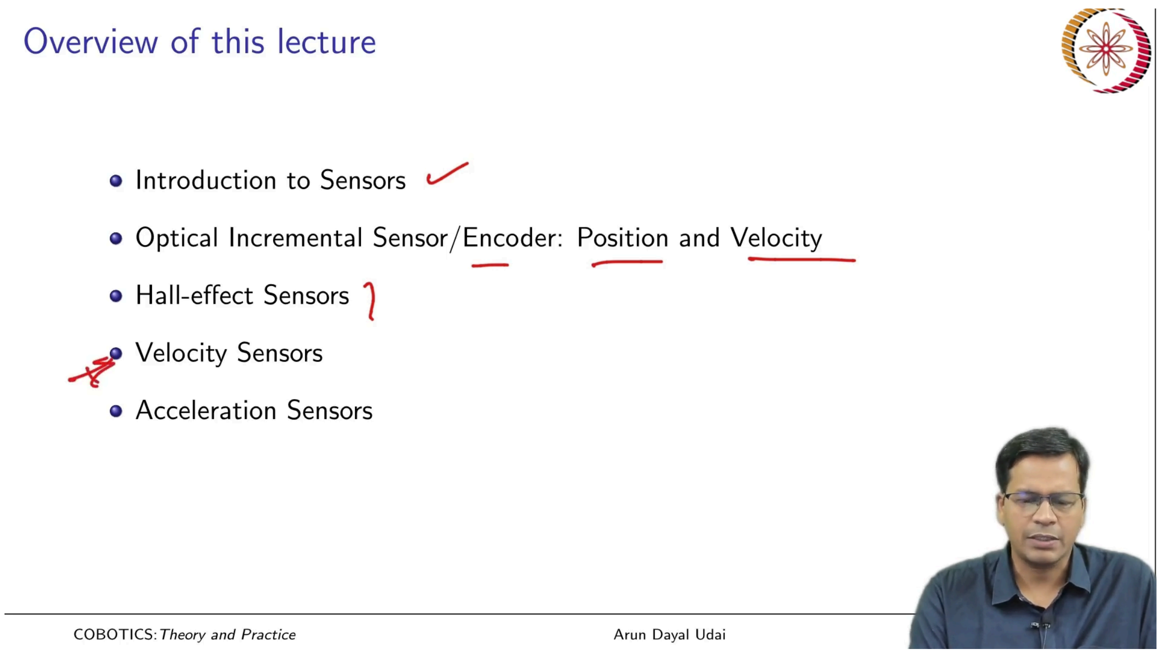
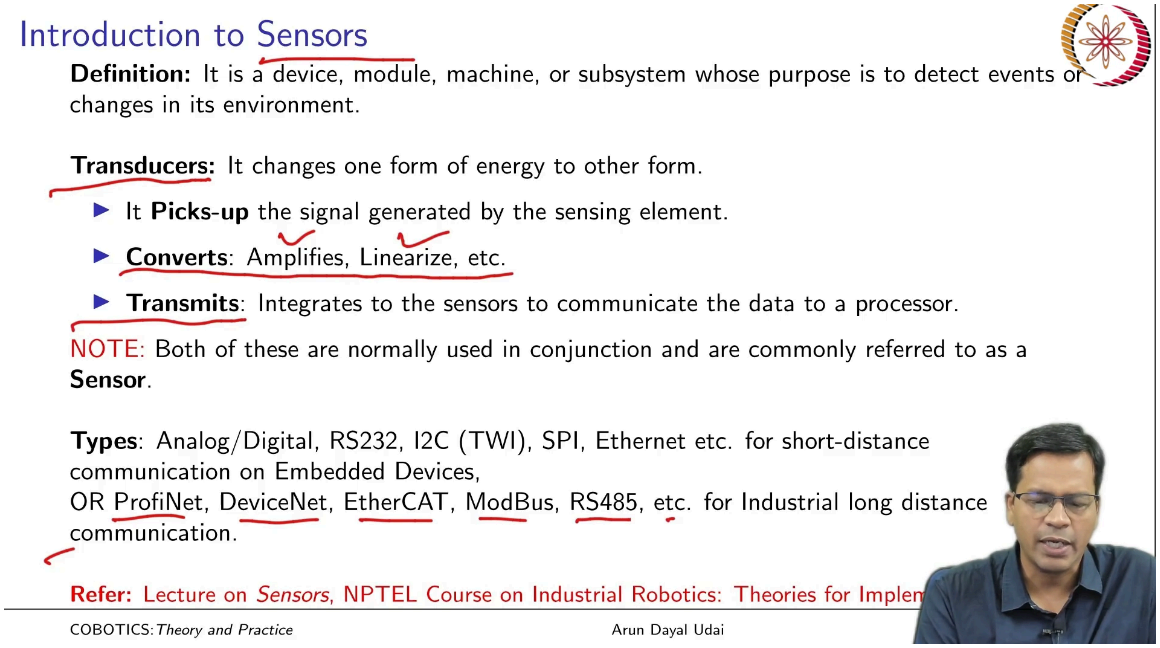
Week: 02
Lecture: 08

Sensors - Position, Velocity, and Acceleration Sensors

Welcome back to the course Cobotics: Theory and Practice. We are running Module 2, which is about Actuators, Sensors, and Safe Workspaces.

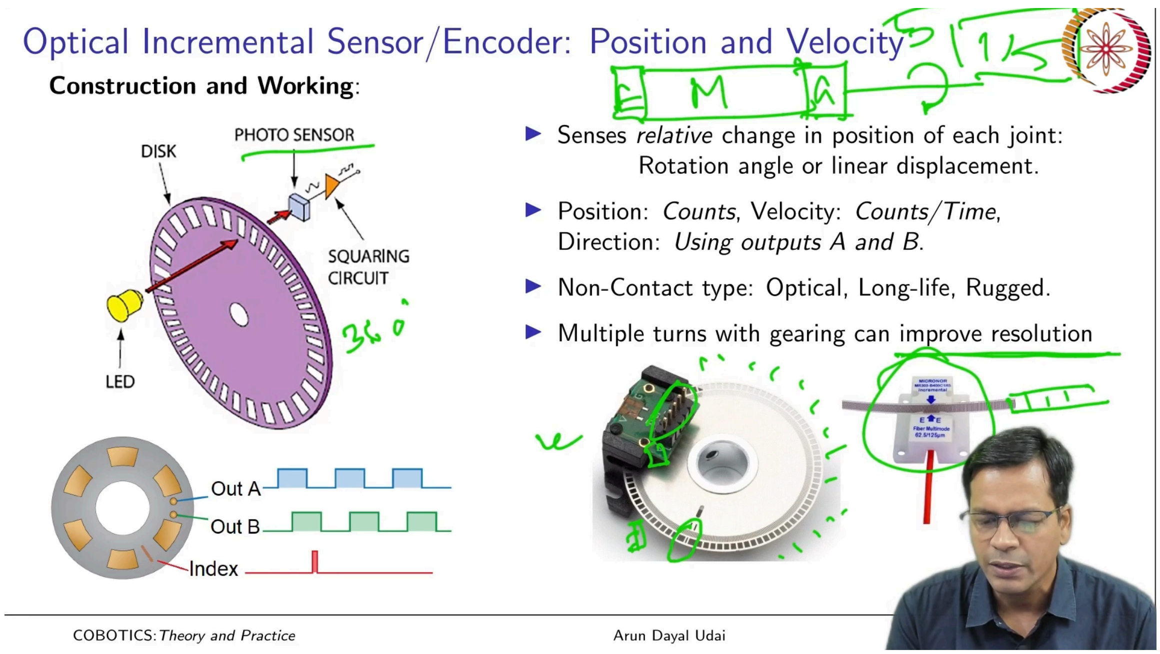


The overview of this lecture is as follows. So, I will start with an introduction to sensors, and I will also introduce you to transducers, which are part of a sensor. Optical Incremental Sensors and Encoders, which are used for position and velocity sensing, will be discussed. I will also discuss Hall Effect sensors, which have multiple applications in various kinds of sensors. Additionally, I will cover velocity sensors and acceleration sensors, which can also be applied for force sensing.



So, let us begin with sensors. So, it is a device, module, machine, or subsystem whose purpose is to detect events or changes in the environment. It includes a transducer. What does it do? It changes one form of energy to another form. So, what are the parts of a transducer? Basically, it picks up the signal generated by the sensing element. It converts from one form to another; that is, it amplifies the picked-up signal. It also sometimes has a linearizing unit, which tends to linearize the input to the output, and it transmits the signal. So, basically, it integrates with the sensor to communicate the data to a processor. So, the transducer basically handles the whole conversion from picking up the signal, which is generated from the sensing element to communicating it to the processor in digital form nowadays. So, it includes all of these. It picks up the value from the environment, which may be temperature, pressure, or displacement. It converts, amplifies, and linearizes it electronically and has an element, which is a transmitter, that transmits it in an acceptable form, which finally goes to the PC or a microcontroller. So, both of these that is the transducer and the sensing element. Both of these are normally used in conjunction and are commonly referred to as a sensor. So, a sensor as a whole nowadays is the transducer and the sensing element combined together as a sensor.

Various types of Such devices can be analog devices or digital devices. Digital devices are basically the conversion of analog signals to digitally accepted forms so that they can be accepted by a microcontroller, a PC, or some kind of embedded device. So, based on that, it can also be analog when you have a continuous range of values ranging from the whole range of the measurement that it can do. It can communicate using RS232, I2C, which is a two-wire interface, SPI, Ethernet, etc. For short-distance communication, normally for embedded devices. So, these types of communication devices may have to transmit the data, or they can use Profibus, DeviceNet, EtherCAT, Modbus, RS485, etc., for long-distance communication, which is mostly common in the industry. So, mind it. Your sensor has the sensing element, the transducer, and the transmitter. The transducer can convert from one form to the other. It amplifies, linearizes, and finally transmits it. So, the transducer again has three forms of conversion, as I have discussed.



So, let us start with the optical incremental sensor, which is also known as an encoder, which is used to measure position and velocity, especially the joint position and the joint velocity in robots.

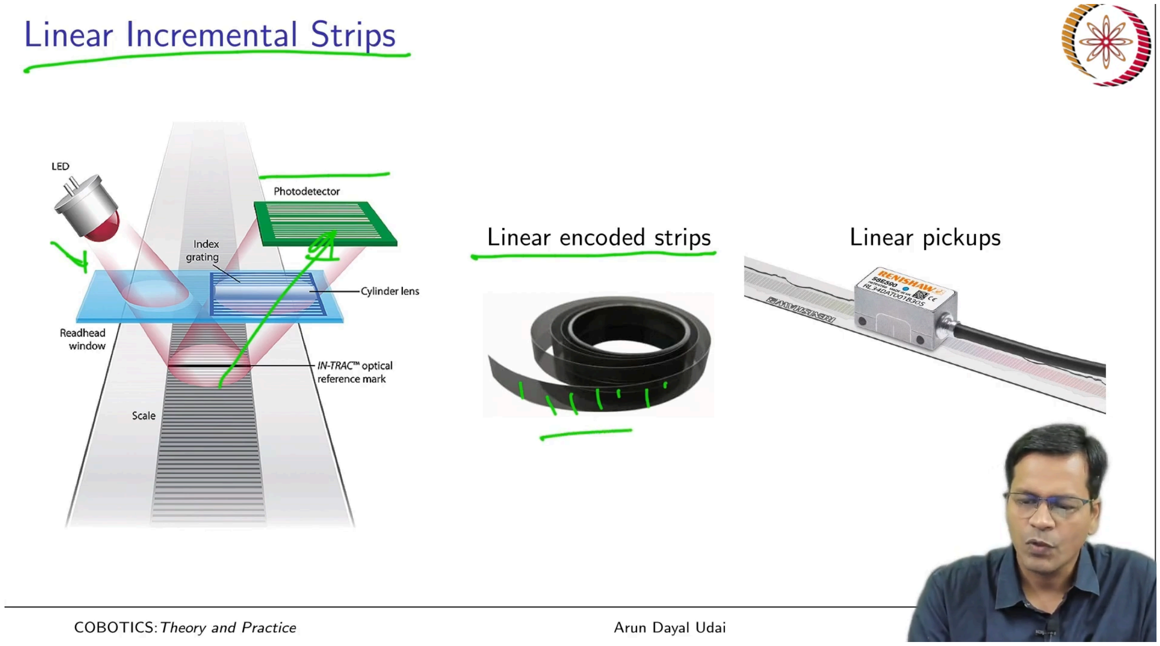
Construction-wise, they are very simple. So, it has a slotted window, which is there. You see, it is a disc with so many windows. There is a light source, normally an LED source, a Light-Emitting Diode, which is here, and there is a photo sensor, which is here, and a Squaring Circuit, which basically converts the analog value, which is received by the photosensor, to a digital form, high and low signals. This setup would simply count the number of windows as this wheel rotates about this axis. If it rotates, what will happen? It will sometimes see the opaque in between or sometimes it would see the green color, which are windows. So, these are windows from where the light can pass through and fall on the photo sensor. Got it? So, effectively, if you have two such LEDs and two such photo sensors, you can have them arranged in a manner like this: two LEDs and two sensors. So, each one of them can give us a square wave output, that is, a high and low signal. As the wheel rotates, you get a continuous signal, which is high and low. So, this is high, this is low, high and low that will continue. And there is a slot which is a very, very small window, and that is used as an index. So, for every complete rotation, this index will pass, and you will get a small high signal only. So, with this, you can count how many turns it has completed.

So, now, this senses the relative change in the position of each joint. So, wherever it starts, let us say this becomes the 0. If it has counted five windows and you have, let us say, 360 total windows in this wheel. So, five windows will mean 5 degrees it has turned. So, it has simply measured these 5 degrees from the starting position. To the new position where it is now, so it is basically a relative change in position which it has recorded. So, rotational angle sometimes these slots can be made even on a strip with small slots which can be there like this and It can even measure the linear displacement of this strip. That way it can be used to measure the linear displacement also. You should know how many windows you have at a particular distance. So, position it can count the position. Simply count it and get the position, or it can measure the velocity.

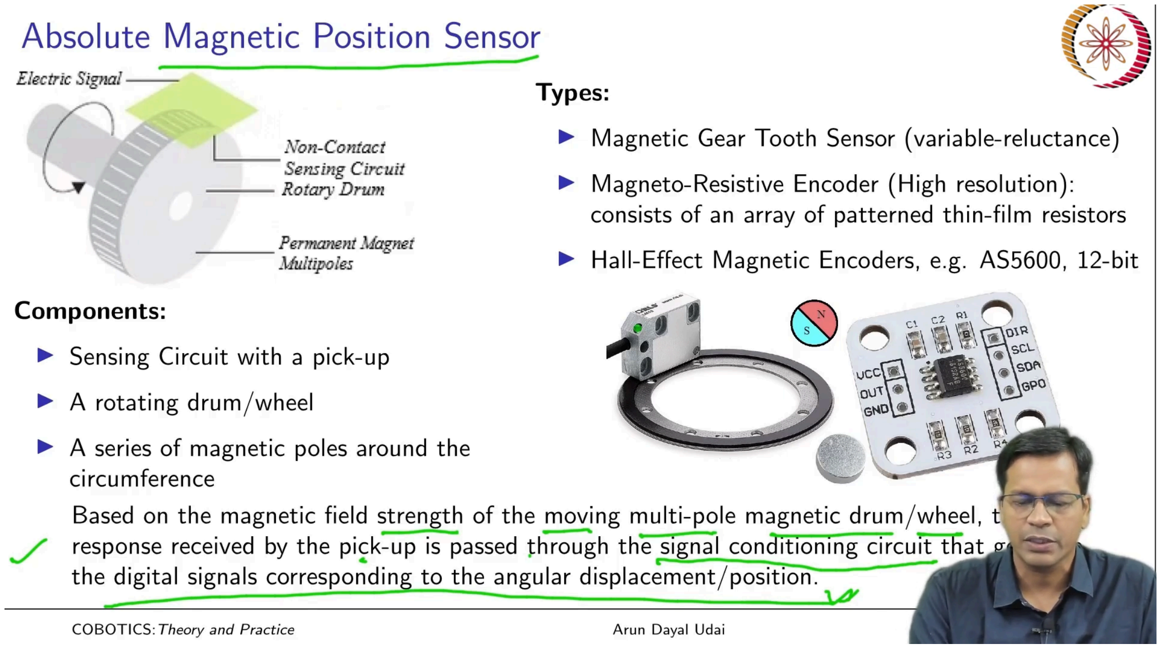
So, the number of windows it has crossed per unit of time gives you the number of high signals it will read per unit of time. So, counts per unit of time will give you the velocity of the encoder wheel, and direction can be noted using outputs A and B. So, A and B are phase-shifted by some distance. So, if it is rotating clockwise or counterclockwise, that can be estimated using the phase A and phase B signals. So, you have two window counters; one is with one LED, and the other one, you will have another one with a second LED and a second photocell over here, and both of them can give you phase A and phase B signals. So, direction, position, and velocity, all three of them it can give you.

So, it is basically a non-contact type. So, it is optically read. So, it has a long life, and they are very rugged.

So, yes, multiple turns with gears can improve the resolution. So, normally, these are fitted at the rear part of the motor. You have seen it earlier. In the case of a DC motor, you have an encoder which is behind, and then you have a gearbox. So, your servo motor consists of an encoder and a motor. This was an encoder, the motor, and the gearbox. So, this was the output shaft. Let us say this is a gear with a gear ratio of 5 times. So, what happens? For every one turn of this motor, you get one by five turns of the output shaft. So, one turn means that if this wheel has 360 windows. So, 1 ton will give me 360 total counts that I can read, but the output shaft has rotated only by 1/5 ton. What it has effectively done is for 360 degrees by five rotations; it has given you 360 counts. So, that is the beauty of it. So, if it is fitted like that, in that case, it can improve the resolution also. So, in the case of motors, normally, it is fitted behind, directly giving you the count. In front, you have a reducing gear, which effectively reduces the speed and increases the torque. So, this is what a physical sensor looks like. So, you see, you can physically see this. There is an indexer here, and there are multiple windows along this circumference. So, you have a set completely. These are the connecting terminals. You may have one side LED, and the other side of it is the sensing diode photo sensor. So, the same in the case of a linear sensor; this is the linear strip with windows; you can see, and one side may have an LED. The other side can have a photo sensor. So, this is how it works.



Linear incremental strips can also work in a different way. Here, it is the reflecting tape instead of transparent tape. So, you have an LED source that gets reflected, and it is read over here by the photodetector. So, there are many such linear encoder strips. They are so dense that they literally look grey-coloured, something like that. So, it looks grey; you cannot see the window so clearly. So, linear pickups are very sensitive nowadays, and you have high-density encoding which is there on these strips.



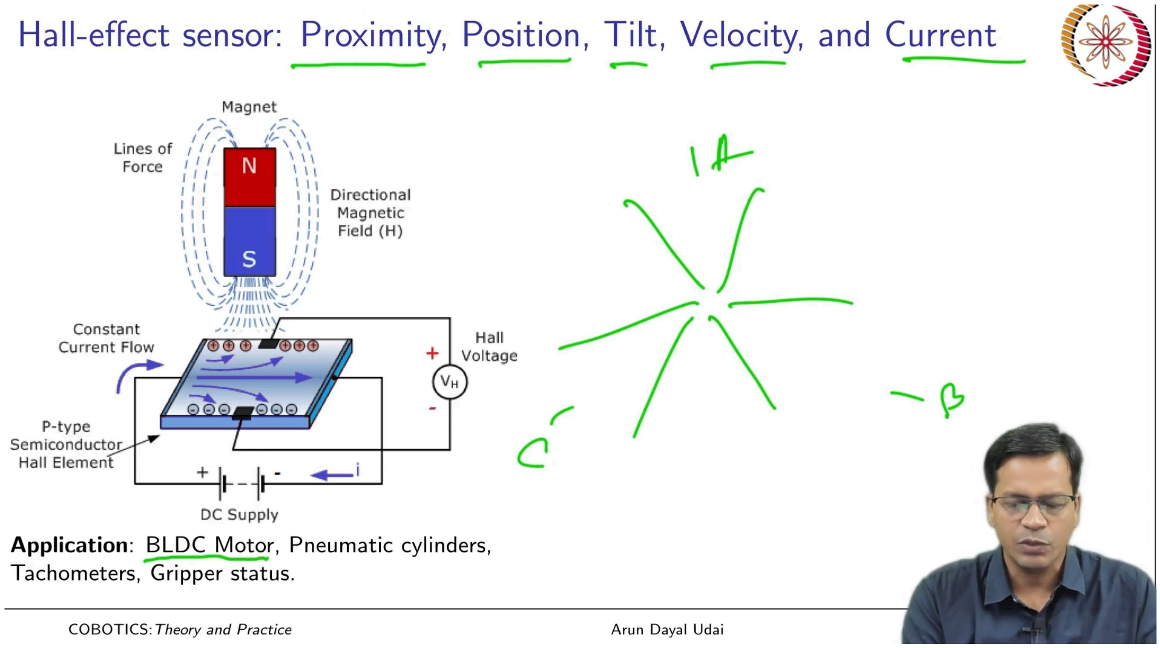
So, now, the magnetic position sensor is again a contactless sensor. So, again, the components are a sensing circuit with a pickup. So, you have a sensing circuit with a pickup which is shown here, a rotating drum with a series of magnetic poles around the circumference. So, these are magnetic poles which are marked here. So, when it rotates, the sensing circuit picks up the counts of how many such magnetic poles have passed by. With that, it can detect the angular position of these kinds of shafts. So, again, this can also be arranged in a linear way, and you can detect the displacement. These are a few types. So, the magnetic gear tooth sensor works on the variable reluctance type, the one which is shown here; it looks like that only.

Another one is the Magneto-Resistive Encoder, which has a very high resolution and consists of an array of patterned thin-film resistors. So, that is Magneto-Resistive, and the first one is a Magnetic Gear Tooth Sensor, which is a magnetic sensor, which is nothing but a variable reluctance. This one is Magneto-Resistive.

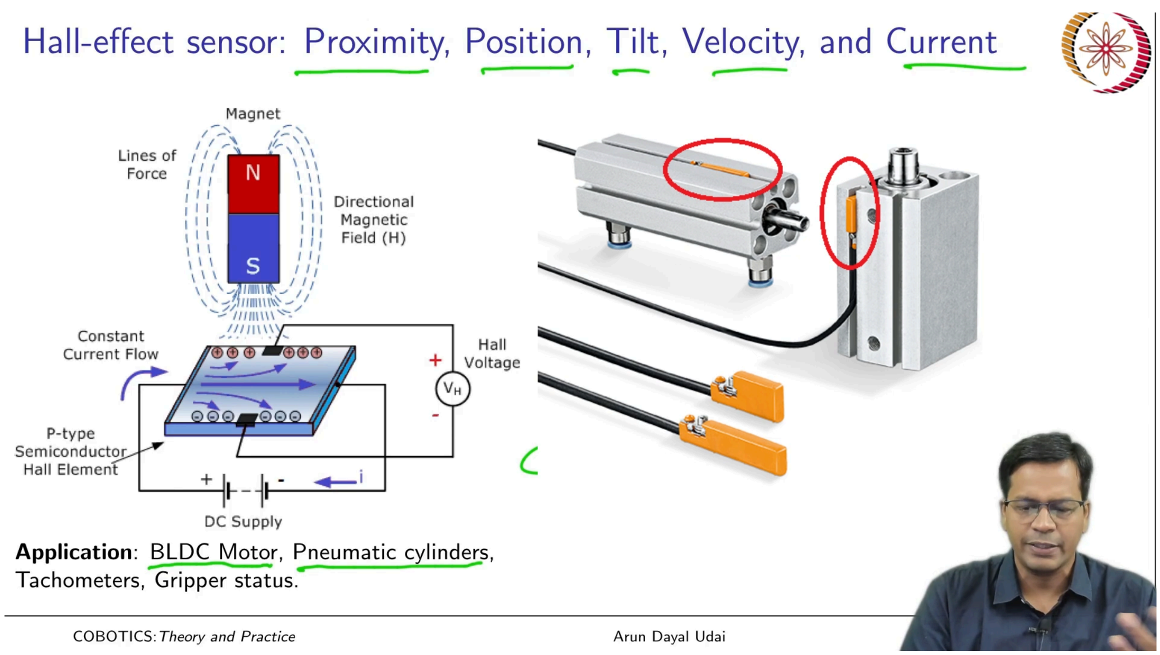
The third one is a Hall Effect kind of sensor, which is are magnetic encoder, as in the case of the AS5600, which is a 12-bit sensor. So, normally, these are widely available for embedded projects; you might have used them. So, it is nothing but a chip that has a Hall effect sensor, and this needs to be glued on top of the So, it has a north pole over here, it has a south pole over here, and when it rotates, this chip can tell you the angular position of this glued magnet. So, this magnet is glued on top of the rotating shaft. So, that angular position can be precisely told. So, this has a set of Hall effect sensors. So, based on the angular position of this north and south pole, depending on the senses that individual Hall effect sensor reads, it detects the angular position of this magnet. Got it?

So, this again, based on the senses, can be further split into 12-bit encoding. And finally, that 12-bit data can be passed using sensors. SDA, serial data, serial clock, and direction everything can be sensed from here using the standard I2C bus. So, it is meant to be used with embedded sensors. Similar ones are there over here, which is shown. This contains a magnetic strip and a pickup, which is shown here. So, this is also quite common in joint sensors. Normally, in cobots, this kind of sensor is very, very common. So, there are various types which are there.

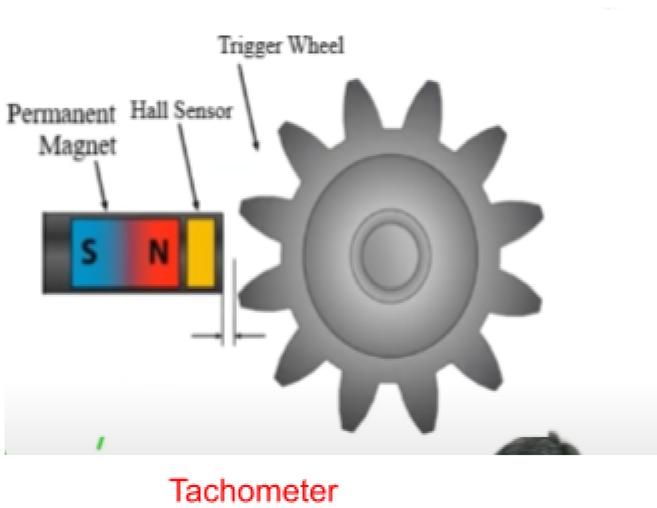
So, based on the magnetic field strength of the moving multi-pole magnetic drum or the wheel, the response received by the pickup is passed through the signal conditioning circuit. So, there is a signal conditioning circuit. It is not so trivial that you can quickly check that circle and estimate the position. There is signal conditioning which eliminates the noise and amplifies it. It filters it, finally segregates the data, and digitises it to generate the digital signal corresponding to the angular displacement or the position, angular position. So, this is how it works, that is, the magnetic position sensor. So, this is very common in cobots. Cobot joints are normally using this. This is the reason it has to be shielded from electromagnetic waves which are nearby, EMI shielding is to be done.

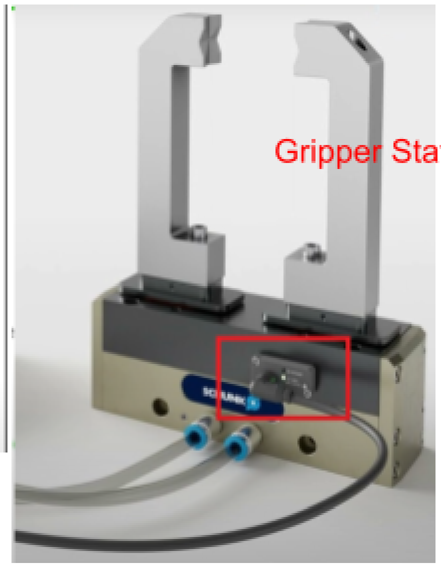


Now, coming to the Hall effect sensor. This is a type of sensor that can be used to detect proximity, position, tilt, velocity, current, and many more. So, this is very widely used in BLDC motors. BLDC motors, you saw you had three sensors, phase A, phase B, and phase C earlier. So, they give the feel of the sector where your rotor is. Depending on the sector, you get to know the position of your rotor. So, it was used for that purpose.

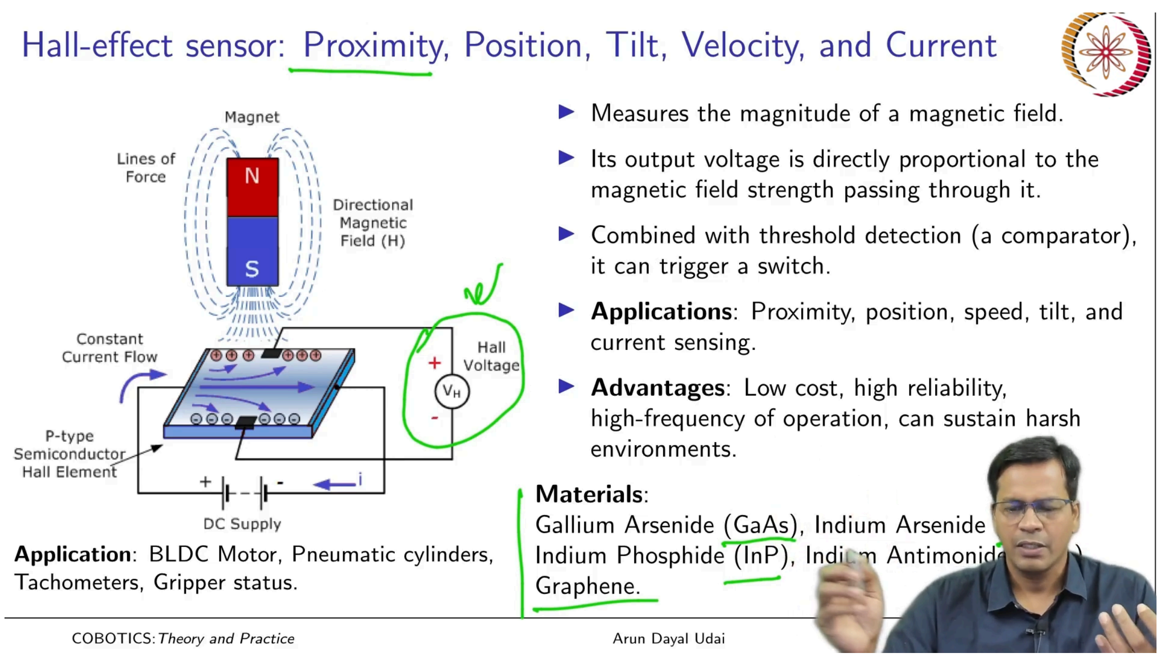


It is also used in pneumatic cylinders to detect where it is, either fully extended or fully retracted. So, you have two Hall effect sensors at each end. Whichever is high is the position of the cylinder.





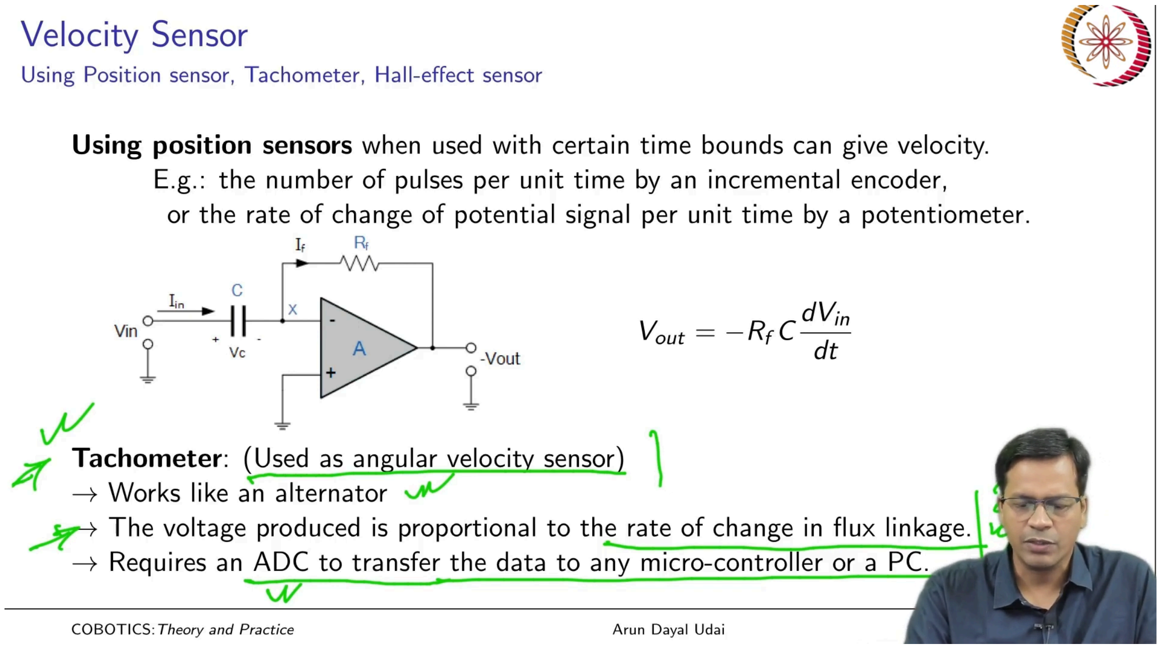
Then, tachometers, gripper status, and open and close can be known. These are a few. There are many other applications of this.



How does it work? Basically, it measures the magnitude of the magnetic field. So, this is just a magnet to create the source here. So, magnetic lines of force are shown here. Its output is directly proportional to the magnetic field strength passing through it. So, this is the Hall effect sensor. The output Hall voltage is proportional to the magnetic field strength that is passing through this material. Combined with the threshold detection, that is, a comparator, it can act like a switch. So, it can trigger a switch. So, Hall voltage is an analog voltage. So, it varies directly with the magnetic field strength that is here. So, you can make it a trigger so that it is thresholded. So, at a particular level, it gives you a high signal; below that, it will give you a low signal. That way, it can be used like a proximity sensor.

Applications are proximity sensor, position sensing, speed, tilt, and current sensing. So, you already know that these magnetic fields can also be because of a current-carrying conductor nearby. So, magnetic fields can energise this also. So, if at all there is a conductor with a current that is near to this, the higher the current, the higher the magnetic field, and the higher the Hall voltage that you can read. So, this voltage now will allow you to estimate the current flowing through any such conductor. Again, if this magnet is used as a tilt sensor, you know this field B will vary depending on the tilt of this magnet. So, maybe you can calibrate this sensor to be used as a tilt sensor. You may have, or you have already used it has a position sensor in the case of a BLDC motor. Speed can also be estimated using that kind of arrangement, as it was there in a BLDC motor.

The advantages are many. It is very, very inexpensive. They have high reliability because they are of the non-contact type. It does not wear out with time, and also it can detect high-frequency operation. That means it can detect very fast. So you can just turn it on and off, on and off. So, a set of magnets can pass by, and you can count each one of them with a high frequency. It can sustain harsh environments also. It is not dependent on dust and moisture also. The only thing is it has to be electronically protected. That's all. Materials that have such properties are Gallium Arsenide (GaAs), Indium Arsenide (InAs), Indium Phosphide (InP), Indium Antimonide (InSb), and Graphene. So, these are some of the materials which are commonly used as Hall effect sensors. Again, this is the sensing element. It gives you a voltage signal. Now, the complete sensor is a package. It will process this voltage signal. If it is inside a proximity sensor, it will digitize this to 0 and 1. It can have a communication circuit also, which can transfer it using I2C or it may be PROFIBUS or PROFINET. So, that communication circuit is within also. So, this is just a sensor, a pure sensor. So, it has to include many other components for processing and transmitting.

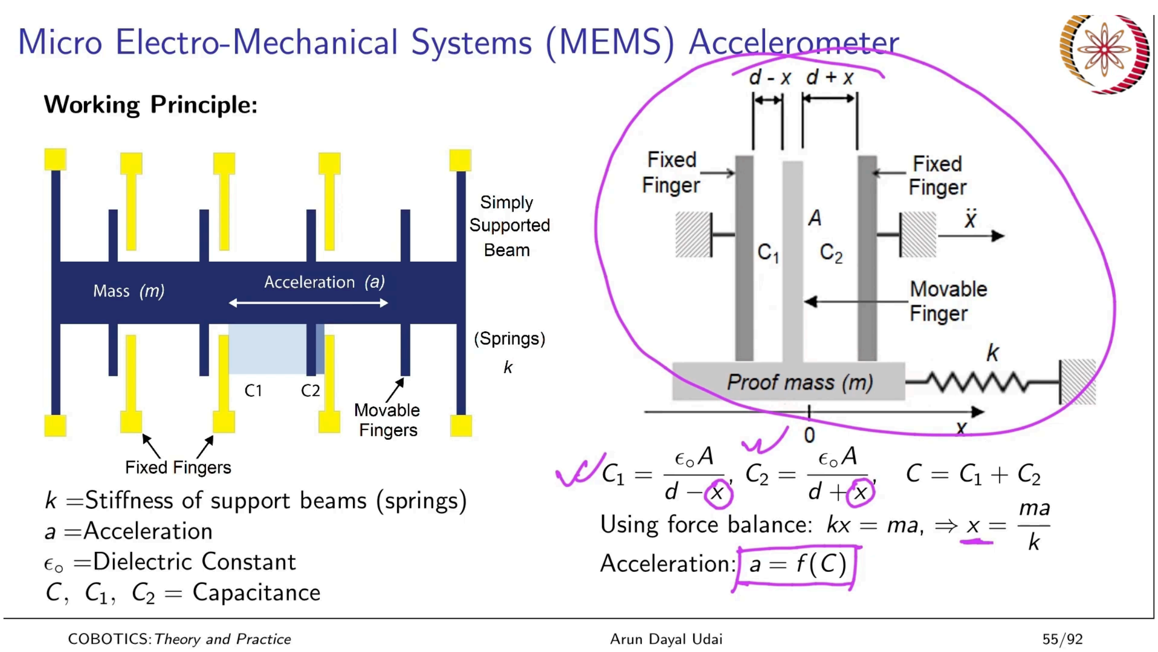


Velocity sensors, so talking about velocity sensors, are byproducts of mostly position sensors, which are also known as tachometers, and Hall effect sensors can be used for that reason. Using a position sensor, when it is used within certain time bounds, it can give you the velocity. So, the rate of change of position is actually the velocity. So, the number of pulses per unit time in the case of an incremental encoder was the velocity. If it is an analog sensor, as in the case of a potentiometer, it gives you a voltage that is proportional to the angular position. In that case, you can simply take the derivative of the voltage signal and obtain the velocity signal. How is that done? This is not; it is just an operational amplifier that is used as a differentiator here. It gives you a voltage output, which is proportional to the rate of change of Vin, Vin is the input signal over here.

$$V_{out} = R_f C \frac{dV_{in}}{dt}$$

So, what is Rf? Rf is the feedback resistance, and there is a capacitor that goes here. So, that comes here, and it is negative. So, whatever the velocity is, the negative of that is reflected here as the voltage output.

So, now, using a tachometer, it is used as an angular velocity sensor. It works like an alternator. An alternator works simply. You know, if you increase the angular speed of the tachometer, a higher voltage is produced. So, the voltage produced is proportional to the rate of change of flux linkage, which is changing because of the speed of the shaft. So, the higher the speed of the shaft, the higher the voltage that is seen by the tachometer. That is very common and is used in quite a lot of industrial applications. It requires an ADC, an analog-to-digital converter, to transfer this data to any microcontroller or a PC. So, a velocity sensor that uses a tachometer normally uses an ADC to convert it to an appropriate form. This tachometer would be a sensor. It needs a transfer of data, so it may have some communication devices also. Normally, a tachometer generates enough voltage, which can be transmitted in the analog form itself.



So, there is yet another very good sensor that can detect acceleration. It is known as an accelerometer, which is known as a MEMS micro accelerometer. That is a micro-electro-mechanical system MEMS sensor. Let us look at that. The working principle is quite straightforward. This is there in school books. High school physics you have learned.

So, let's say you have two parallel plates, which are here, and there is an intermediate plate which is here. If it is a capacitor, what will happen if this plate moves? The capacitance, which is here and here, changes. C1 and C2 change. So, if there is a capacitance change in a capacitance sensor, it can detect the change in capacitance. It can estimate the position of this. So, using this principle, it is designed. So, you have multiple such plates which are here. So, the yellow ones that are shown are the fixed fingers. They are like a comb. So, they are fixed fingers, and you have the blue one, which is shown here, that is on a simply supported beam. These beams are fixed over here, and now this mass, which is here, is a moving mass that can oscillate. If you make this object, the whole assembly go like this: you shake it, so this mass, which is known as the proof mass, moves within, and altogether, it is cut using a single silicon wafer. So, k is the stiffness of the simply supported beam-like structure, which behaves like a spring. a is the acceleration of this mass, which is the proof mass. Epsilon 0 (ε_0) is the dielectric constant of the medium, which is present here in these white spaces. C1 and C2 are the capacitance of the two sides of the beam. This comb. So, this side has C1, and this side has C2 capacitance.

Now, let us look inside. So, you see, this is a proof mass, which is floating on a spring of stiffness k. C1 and C2 are the two side capacitances. So, these are the fixed fingers, and the blue one is the proof mass; this is the moving finger. So, one side of it, let us say if this whole assembly is made to move with an acceleration of x double dot. So, at any instant, let us say it has displaced by a distance x from the mean position. So, one side of it will have the distance between the parallel plates, which is here is d minus x, and the other side will go d plus x. d is the mean position distance that is equal on both sides. So, the capacitance on one side will become epsilon 0 A by d minus x.

$$C_1 = \frac{\epsilon_0 A}{d-x}$$

What is A? A is the area of those plates. d is the initial distance. x is the displacement because of this acceleration.

$$C_2 = \frac{\epsilon_0 A}{d+x}$$

So, on the second side, you see the capacitance becomes epsilon 0 A by d plus x. So, on this side, you see the capacitance has reduced, and on this side, the capacitance has increased. So, the total capacitance, because they are in parallel. So, it will be C will be equal to C1 plus C2. So, the total capacitance will be C1 plus C2. So, using the force balance equation, what you can estimate is kx, where x is the displacement of the spring that creates the restoring force that should be equal to the force which is generated due to the acceleration, that is, ma.

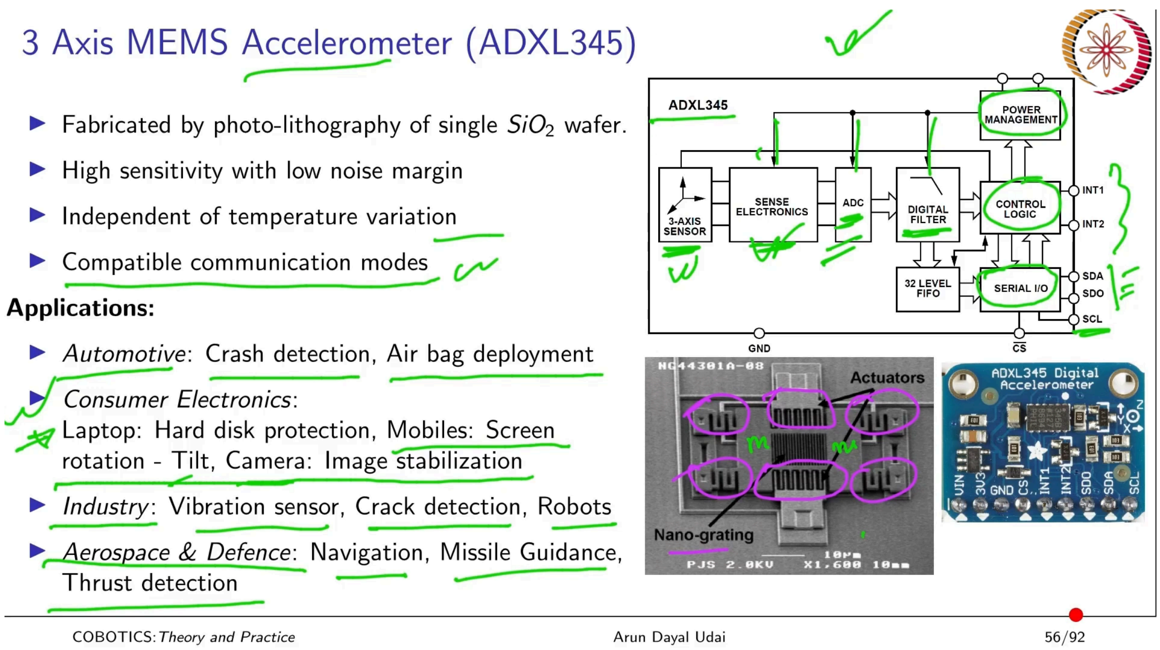
$$kx = ma$$

$$x = \frac{ma}{k}$$

So, kx is equal to ma, so it becomes displacement x is equal to ma by k. Now you see x is the variation that goes here that is changing the capacitance. So, effectively, acceleration becomes the function of capacitance.

$$a = f(C)$$

If there is a circuit that can detect the change in capacitance and create the sensors out of it. So, what happens? So, the whole of this system is a mechanical system. It creates an electrical change in the circuit. So, accordingly, it can be detected, and the signal can be converted and transmitted. So, the whole of this becomes a sensor. Effectively, what is it sensing? Acceleration.



So, the whole of this is fabricated by photo-lithography on a single SiO_2 wafer, a silicon oxide wafer. It is very, very sensitive with a low noise margin. It is independent of temperature variation because the whole of the circuit is embedded within a chip, which is known as a MEMS chip accelerometer. A common one is ADXL345.

Applications are many. It looks like this. You see this is the nano grating that you can see. This is the comb system, which is here, and you can see this is a spring-like structure that is made here on both sides, and overall, this becomes the proof mass, which is here. So, the whole mechanical structure is sitting inside, inside the chip, and there are many other conditioning circuits that go inside, as you can see here. So, you have sensor sense electronics which converts it to the analog form. An analog-to-digital converter is there, and it is filtered, and its power source is there for each of them. Control logic is there, and you have a serial input and output system which is here, which finally converts the signal to SDA serial data, that is I2C, and it is transmitted. So, the clock signal is here, data input and data output are here. So, there are also interrupts that may be generated from here. So, this is ADXL345 chip details. So, you see, there is a sensor sensing element, that is MEMS mechanical system. You have sense electronics that detect the change in capacitance, convert it to digital form, filter it, and transmit it. So, the whole of this is the accelerometer sensor. So, this you see, is independent of temperature variation because it is packed within a vacuum inside the chip. Compatible communication modes are there. It can be I2C, it can be SPI, it can be UART or various other forms in embedded.

It is used for automobile crash detection. 2G, 3G, 6G sensors are there for airbag deployment. Consumer electronics for hard disk protection: if a hard disk falls, it automatically parks, so that is used also in laptops and mobile screens. Rotation, that is tilt sensor, and three-axis accelerometers are also there. Based on the components of G along all the three X, Y, and Z directions, you can estimate the tilt also. So, Gx, Gy, and Gz are sensed by the three directional, three orthogonal accelerometers. Those are picked up, converted to tilt, and that becomes a tilt sensor. Tilt sensors are used in cameras for image stabilization, that is, to detect vibrations and stabilise the image. In industry, they are used as vibration sensors for crack detection in robots. In aerospace and defence, it is used for Navigation, Missile Guidance, Thrust detection, and many, many more. So, you see, this is one of the very versatile kinds of sensors, that is, the accelerometer. It is a MEMS device, and they are very, very small. It saves a lot of space.

So, we have now discussed various types of sensors, especially position sensors, velocity sensors, and accelerometers. In the next lecture, I will discuss force and torque sensors. We will discuss transmission that is, using planetary gearboxes and harmonic drives. That is all for this lecture.

Thanks a lot.