NPTEL Online Certification Courses
Industrial Robotics: Theories for Implementation
Dr Arun Dayal Udai
Department of Mechanical Engineering
Indian Institute of Technology (ISM) Dhanbad
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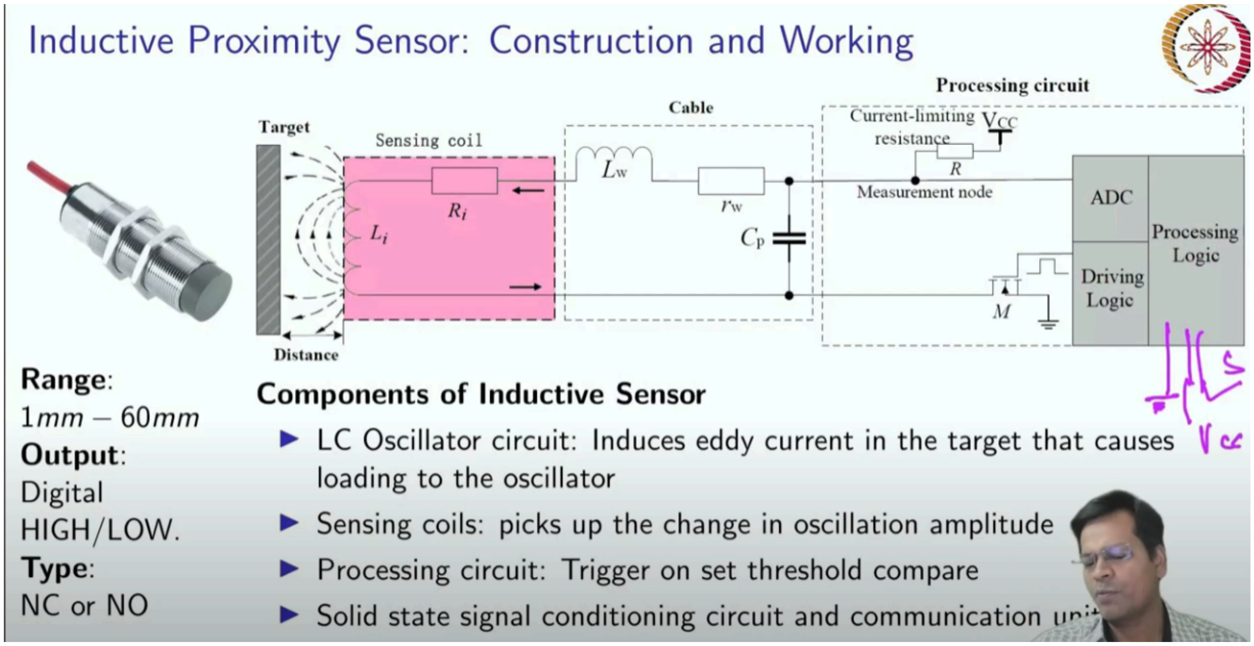
Non-contact (Inductive and Capacitive), Force/Torque Sensors

Hello, and welcome back. So, in the last few modules, we have studied different types of different components of robots, maybe a few types of sensors that we have learnt, few types of actuators we have learnt. We are now introduced to robots, almost. So, continuing further with the sensor module, we have already gone through position sensors, various types. We have seen how a velocity sensor works. We have seen an accelerometer and how it can be used like a force sensor. Continuing further, today, we will go through a leftover portion of that, that is, the proximity sensor. That forms a very important type of sensor which just checks the events, just checks the events which are happening around. It just tells us whether it has happened or it has not. So, instead of going in an analogue way most of the time, this type of sensor works like a digital sensor, just as an indicator. So yes, today we will be discussing upon inductive sensor. We will discuss capacitive sensors and a few types of force sensors. That is, one very broad class of force sensors is strain gauge-based, which is most widely used in the industry also, so we will be discussing that.

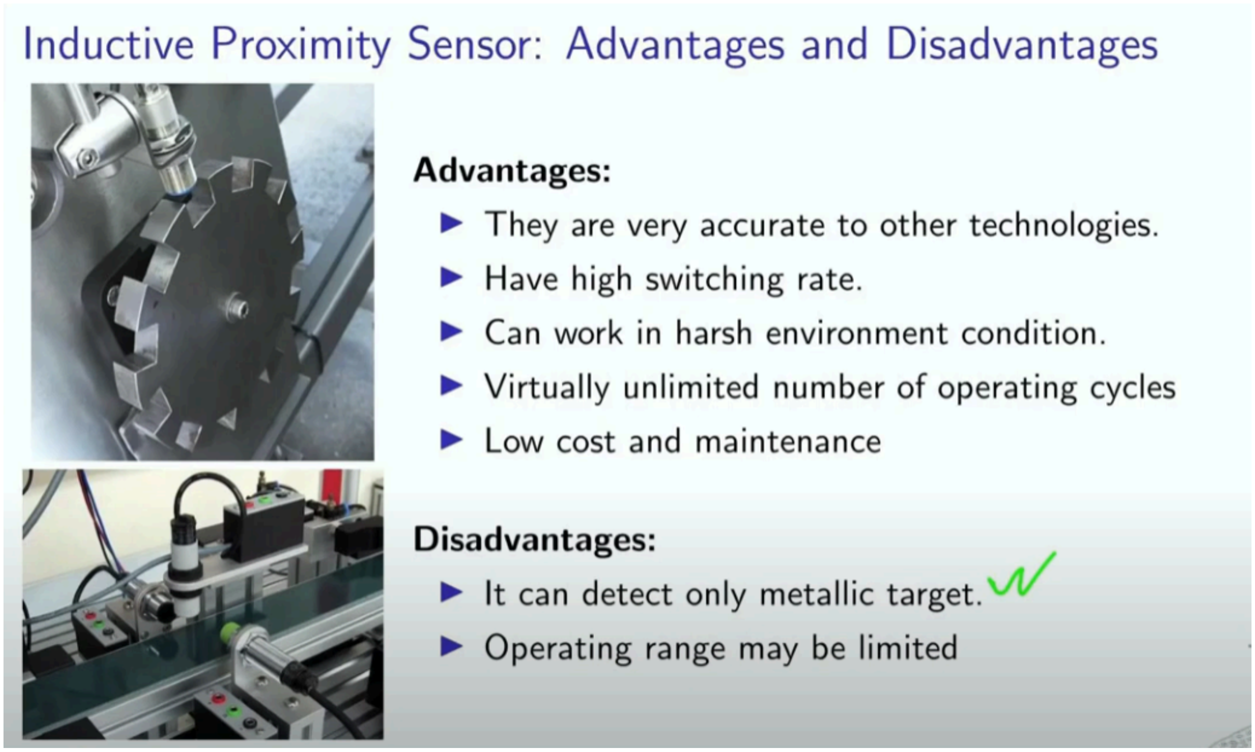
So, let us move ahead. So, to begin with, we will start with the non-contact type of sensor, that is, inductive and capacitive sensors.



The inductive proximity sensor works very much like our induction heater at home. The first part of the sensor that you see here is this one (sensing coil). So, overall, it is part of a circuit which is here that may be called an LCR circuit. So, if it is an LCR circuit, any current which is there cannot be just static. If you just start with an oscillation, it is very much like a spring-mass system. So, provided with some external energy that is provided through external supply, there is an oscillation which is happening all the time over here. So you have a current oscillation, which is there, and that is picked up across the capacitor, which is here. And you have a coil which is here. You have a coil, which is here basically an inductive coil, so it transmits flux outside to it, transmits flux outside the sensor also. So anything if it comes here which is a metallic target, if it is there, so if it finds any metallic target somewhere nearby, there is some change in flux, obviously. So, it is treated like a load for this type of sensor, and there is some change in the behaviour of the loop current, which is oscillating inside. So, there is some internal oscillator. There is some resistance which is here. There is a capacitor which is here across the capacitor. I am just measuring the voltage. This measured voltage is not just a source where we can measure voltage. So, it is also supplying to this LCR circuit, the external power which is there. Finally, this sensed voltage is not significant enough to be transmitted, so it is converted to a digital form using an analogue to digital-converter, and there are some. Driving logic comes from here. That may be a triggering circuit. So, if at all we want to count the event, we need to have a switch which can give me a square wave kind of signal which is finally picked up and transmitted using this processing logic. So this is a gross layout, not exactly this one. The internal circuit may be quite complex, but not this one. This is just to get the philosophy of it that you have an LCR oscillator. You have an LCR oscillator with an induction coil over here. OK, So any target in front of it will change the oscillation frequency or the behaviour of the voltages which are available over here. So you just pick up that voltage, you convert it, you make it, make a switch, trigger a value of in a way like high or low, and finally that is transmitted. So this is how it works. It can work within the range of something around 1 mm to 60 mm. that is the normal range. You may see a few more mm, which may be covered by some manufacturers. OK, So, the output is normally digital, and that is in terms of high or low signal. In industry, it is like 24 volts or 0 volts. Yes, it can be normally closed or normally open. What does it mean in any digital sensor? So, if at all there is a target, it gives you a high signal. It may be possible that you use it like normally the signal is high. If it sees any target, it turns too low. So, either way, it is possible.

So, just look at the theory now. So, it has an LC oscillator circuit. LC is L for inductance, C for capacitance oscillator circuit. It induces an eddy current in the target. It is like an eddy current that is coming here due to this flux which is changing here. So, it induces an eddy current here in the target. That causes loading to the oscillator. So you must have noticed when you put a utensil on top of your induction heater, then only when it turns on it detects the target, so that it is loaded, and then it starts drawing electricity from your source. So, the same way it is. It is loaded, and that load is now checked at this target point.

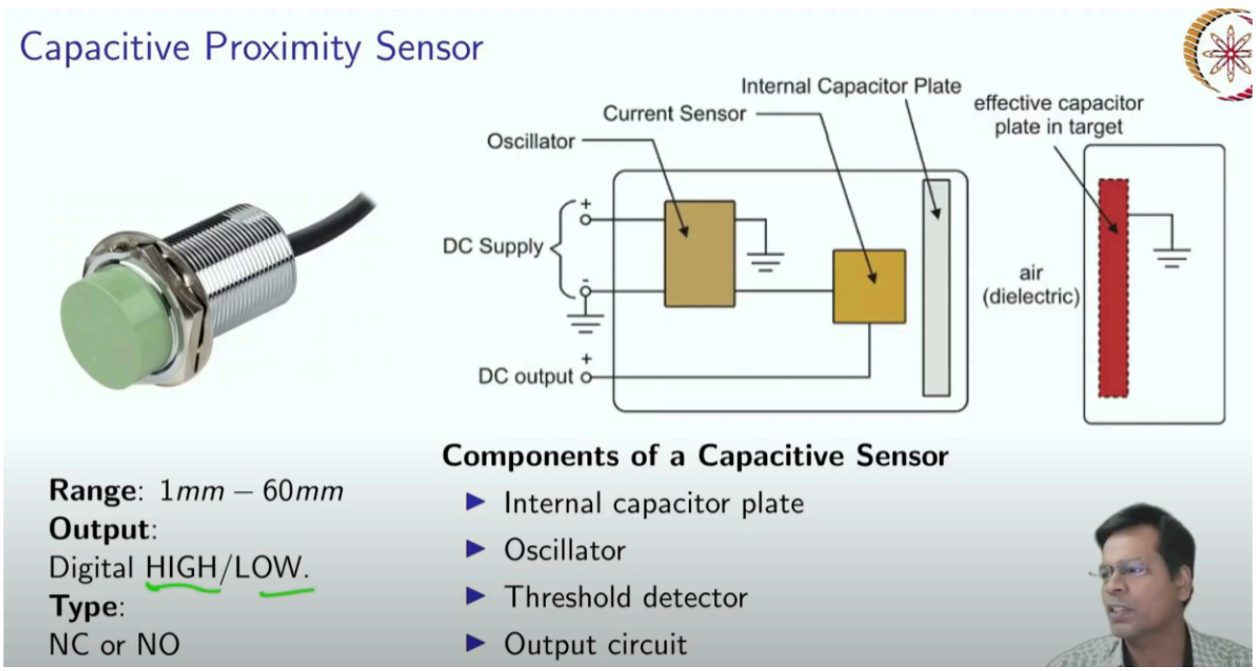
So, this is the point across which, if I keep on checking the voltage across that, so I can come to know, I may come to know that, yes, there is something which has come now. This is how it is triggering the circuit. So, the sensing coil that picks up the change in oscillation, amplitude change in oscillation is picked up, and finally, it is processed, and the trigger is set. OK, a trigger level is set as a threshold compare level. It is normally an op-amp comparator, which just checks if the value is above a certain threshold. You give it a high signal. OK, So yes, this is normally a solid-state signal conditioning circuit. OK, and a communication unit. So there is a communication unit which can transfer it like a digital signal, high or low, or it may be a simple another way of conversion, sometimes like I to signal, or maybe a serial signal or something like that. But that is not much necessary here. You just have three wires: one to connect it to the ground, the other one to voltage, that is, the supply voltage, other one is ju.St for the signal, OK. So these are mostly the three wires which are there. So look closely, it looks very much like this, OK, very much like this, OK. So it has two cross nuts which are there, so you can have some fixture over here to hold it in place, OK, so that you can tighten it and place it thoroughly. And then normally, they have three wires at the end, three wires as I told you. So one of them is the supply voltage, which is 0 to 24 volts, OK, So yes, and this is the 0 volt, that is the common one, which is ground, and one of them carries the signal-digital signal out may normally be open or closed type. So, this is what it looks like, OK.



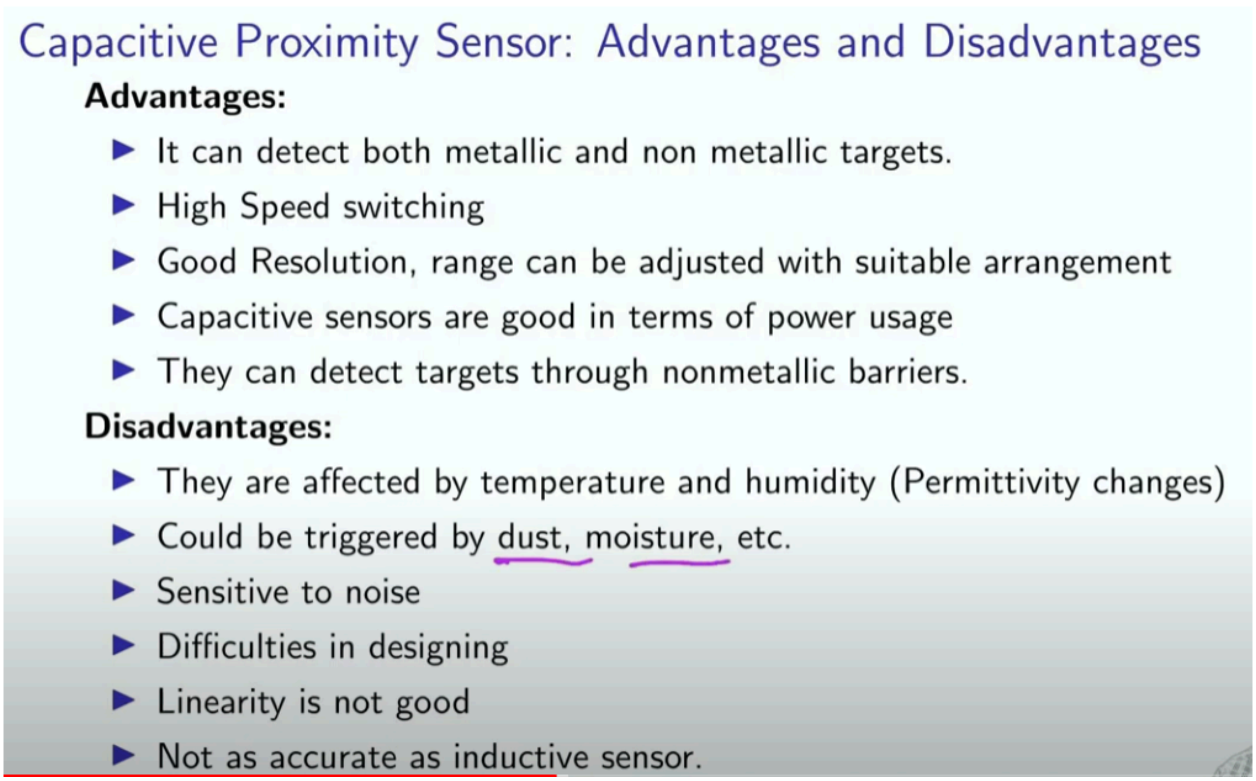
So, yes, this inductive sensor has got few advantages and a few disadvantages that we will be discussing now. So these are very, very accurate as compared to other technologies- OK, which are there in the industry, like capacitive sensor, maybe ultrasonic sensor, OK. So, as compared to them, these are very, very accurate, and they have a high switching rate. Why is it required? Maybe. You have just like this one. You have a conveyor here which is carrying different objects on this floor, OK, and then you have multiple types of sensor from the top, from this side, OK, So all these may be capacitive, may be inductive sensor. Those are all proximity sensors because this platform, which is a moving conveyor, is quite wide. So, you may have different sensors from all around so that you do not miss out on any object which is moving on it. So, this is one may be a possible arrangement. Another one is a flywheel, a flywheel which is rotating, and you have this kind of protrusions which are there. So, what are these? So, they are the object. They behave like objects if they come closer to this proximity sensor which is here. So, it will count it as high. So, a number of high counts will let you know the position of this rotating flywheel. So these are a few arrangements and some applications. That is there in the industry quite commonly. So, yes, now you see if this shaft is rotating at very high speed. What will happen? You will see a very high frequency of high and low signals. OK, So if this inductive capacitor does not have this high switching rate, it will behave like a constant high signal which comes at a high frequency. That should not be the case. So this is the reason why a sensor, a proximity sensor, should have a very high switching rate. OK, So it can work in a very harsh environment, so normally industrial environment like this. They have vapours, and they have moisture, they have dust, they are prone to noise. So, this kind of environment is very easily accommodated on

at least an induction sensor. OK, inductive sensor. So virtually unlimited number of operating cycles because nothing changes within the circuit.
Right, So nothing is getting wear or worn out over time because there is no physical contact, which is there. Not even the internal source is there, which is changing its amplitude also. So everything remains inside intact, and nothing is changing. It is a solid-state device. Normally, these types of sensors have an unlimited number of operating cycles, so over the period of time, it almost sees years, OK. So yes, they are very low cost because hardly there is any circuit. You can create your own circuit at your lab, and you can just test this kind of circuit. OK, So yes, they are very low cost. They have almost like no maintenance. You just need to fit it and forget it.

There are a few disadvantages. Also, It can detect only metallic targets. The way it works at a current can only be induced on a metallic target. So, that is the reason it works only with the metallic target. That covers a wide range of objects which are there in the industry. So yes, it works quite commonly with those. So, the operating range may be limited. Yes, because you see at a current that flux lines cannot go quite far apart, or it may not be dense enough to trigger that change. OK, So that is the reason. This is not quite the case. They do not have much longer range.

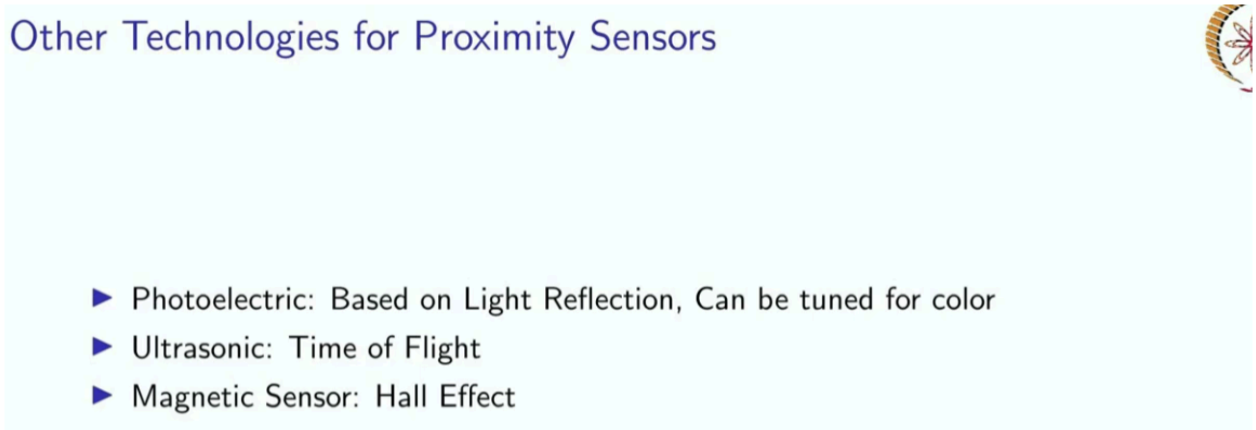


Now, going to the capacitive sensor, this is almost similar way. It works with a similar range and similar output type. This also triggers a level somewhere within the LCR oscillation circuit. So, just like the earlier one, this also has an oscillator. This also has an oscillator circuit that is sent to a current sensor, which is here, and there is a capacitor plate, which is here. So what is creating that change is this internal plate. This internal plate capacitor plate works like a capacitor, along with the external target. If at all you see a target, there is a capacitor. If at all there is no target which is nearby, so there is no capacitor. And this air in between. This works like a dielectric. So yes, you see now the target. If it comes closer, the capacitance changes. The capacitance which is here. This changes. That creates a change in the coil frequency and the threshold voltage, which is there. So, yes, that also is picked up somewhere, and it is detected like a threshold beyond, which you just have to give it a high signal, and finally, they are given out with the form of the sensor, like a DC output. So, philosophy remains the same. The only thing here is, instead of using an inductor. Now, you are using a capacitor that changes. So, yes, the internal capacitor plate is there, and you have an oscillator, which is there, and there is a threshold detector, which is there, just like an inductive sensor, and the output circuit simply allows it allows the data to be transferred to longer distances. It changes the level from 0 to 24 volts. So 0 or 24 volts if it is digital, so it is a high or low signal.



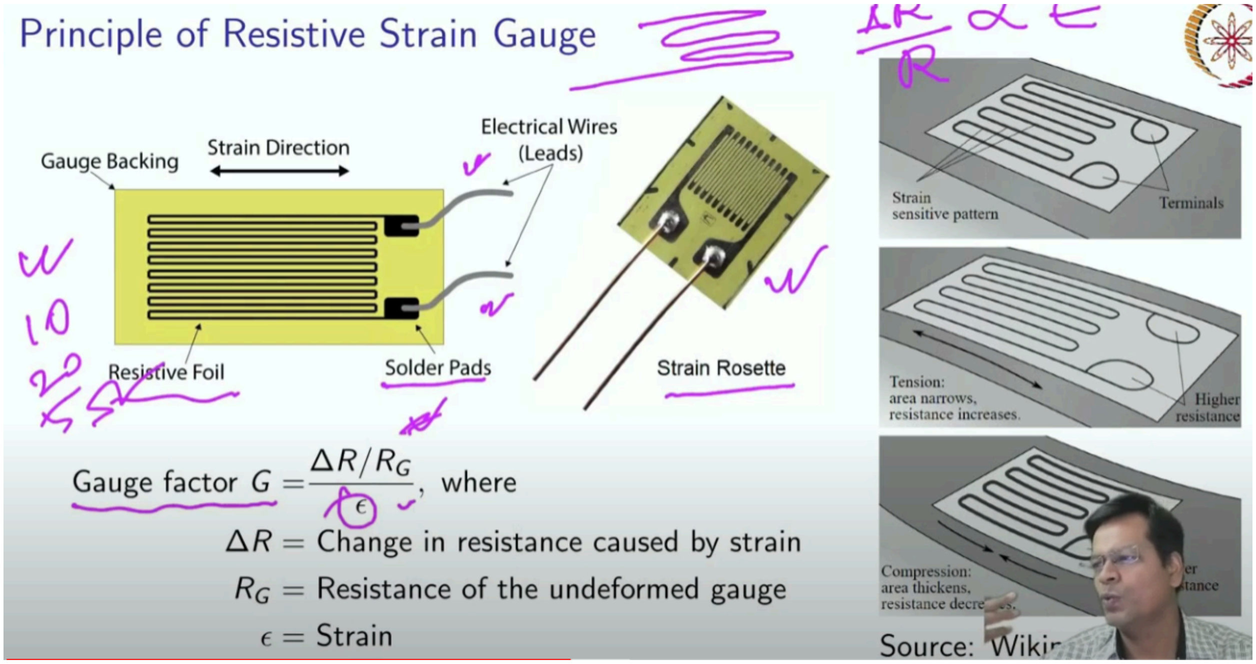
So, yes, we will also discuss some advantages of this. This can detect both metallic and non-metallic targets. How? Because anything which comes in front of it may be moused, which is there somewhere nearby, so that also can change the dielectric constant, which is there, So it can detect the change very easily, even if it is not a metal. High-speed switching. This has a v.Ery high-speed switching, just like an inductive sensor. I think it is even better for this, OK, So it has a very good resolution. The range can be adjusted. Let us say you are now sensing from 0 to 5 mm. You can adjust with some potentiometer, which is there sometimes on top of this kind of sensor, So you adjust that. You can adjust the range from 5 mm to 10 mm, 10 mm to 20 mm, so anywhere in between work. They are very good types of sensors in terms of power uses. They hardly consume any power when it is idle. It is also used on mobile devices and mobile robots also because they carry a battery along with them, so you have to work with a battery for quite a longer amount of time. They can detect targets through non-metallic barriers also. What does it mean? Let us say you have a sensor. You have a sensor which is expecting an object somewhere over here. Any object can come in this range. But fortunately or unfortunately, you have a barrier which is here, and this is a non-metallic b.Arrier, OK, So even if this object comes now with this barrier over here, it can detect. If it comes here, there may be some change in the tuning distance, which we have done. Let us say I have tuned it to work with 50 mm over here. Now, it will work with a lesser distance, maybe 25 mm. Now the object has to come in order to get detected, OK, So, that distance may vary. But, yes, it can use that kind of thing. This allows you to seal the whole of this sensor within the robot, so it can be made a very good IP enclosure, Ingress Proof Enclosure, so that dust and water that cannot get into your robot. So yes, because anyway this type of sensor, capacitive or inductive, they carry solid state devices inside. They have very good ingress protection. They range from IP 65, 67, and sometimes 68 also.

So, a few disadvantages are there with this capacitive sensor. They are very sensitive to temperature because it changes the dielectric constant of air. So, the range can vary if you have tuned for a certain distance. So, with the increase or decrease in temperature, that distance may vary. And same is the reason: it changes with humidity because of the permittivity, which is there that changes the air which is there in front of it. So, it can be triggered by dust, it can be triggered by moisture. This makes it a little unreliable as compared to the inductive type of sensor. OK, And they are very, very sensitive to noise because it is a capacitor, just like your radio tuner, if you know it. They were also very, very sensitive. They work on a capacitor, so any vibration in the plates will create unwanted triggering of this type of sensor. So, they are sensitive to noise. It can turn it little unstable at times. So just, they are normally placed on fixed installation. Yes, difficulty in designing, but we hardly do it when we are in the industry. This is for academic mission. Yes, to understand yes, constructing such a fine-tuned circuit is really very, very difficult. So linearity is not good. So, if you think That you can detect precise distance by tuning this, it is not that linear to plan that, OK? So, they are not as accurate as inductive sensors, as you know the way it works. They are not as accurate and sometimes not that reliable, also because of these reasons.



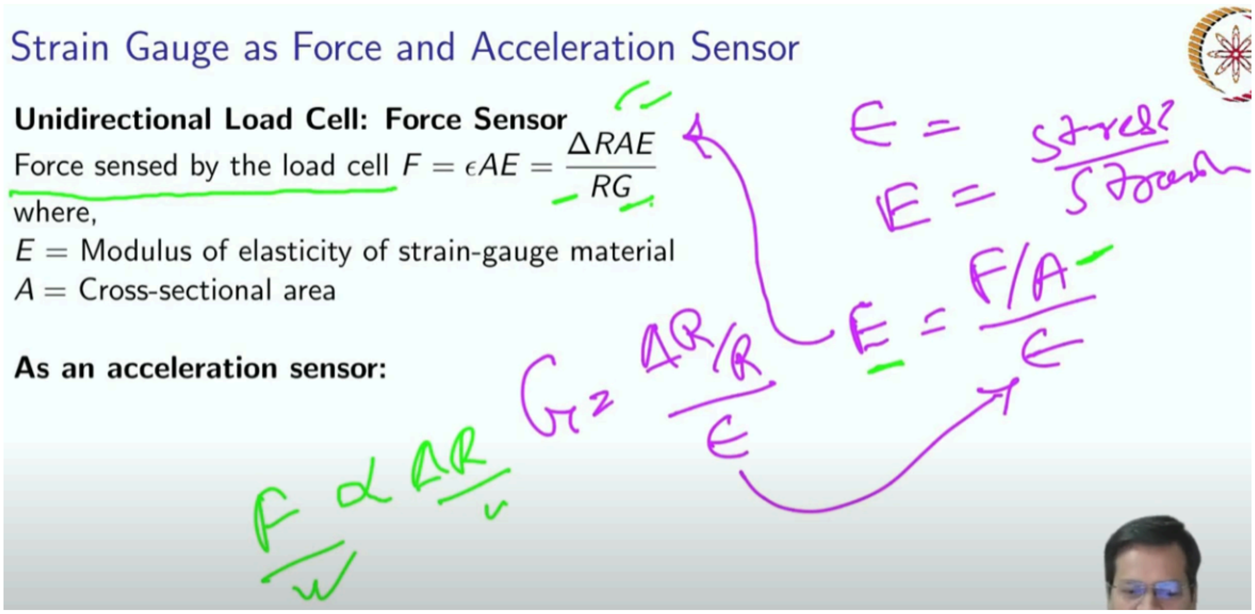
Not just these. There are many other types of proximity sensors which are there in the industry. A few of them are photoelectric. One photoelectric one is there in front of your mobile phone also, so as it comes closer to your ear, your front screen gets turned off. So, it does not detect any touch by your fingers or sometimes your cheeks and maybe your ear, so that is the reason they are based on light reflection, and they can be tuned for colour. That is the beauty of this, but not that accurately. The same colour may have different intensities and will behave differently. But yes, in industry, in a controlled environment, it can be tuned for colour as well. So that is the beauty of it. And ultrasonic sensors, which are based on the time of flight. It sends out the ultrasonic waves, and it just detects the reflected signal. They can also be used as a distance sensor to some extent. Yes, magnetic sensor, hall effect sensor-you have already seen earlier, so all these can behave like a proximity sensor.

So yes, now moving ahead to a very wide kind of sensor which is a force sensor, torque sensor, that can be used like an acceleration sensor also. So, using the Strain Gauge is a very common one, a very rugged one, and for quite a long time, that has still been there in the industry because industrial robots demand a rugged kind of sensor. This is the one which is used, So it can go as high as six axes, which can detect forces in all three directions and torque in all three directions, orthogonal direction. So, it can be unidirectional also. So we will just move on, and we will see how it is.



So, yes, what is this? It is nothing but a standard resistance, resistance coil which is just arranged in a way like this, and from the top. And from they are put in a sandwich kind of thing. So, from the top, there is a foil, and then you have a resistance coil. In between you have another layer of foil which covers this inside so that it does not get distorted or damaged. This is what it looks like. This is a resistive foil, so two leads are there, just like any other resistance. 2 leads are there. These are solder pads, or they may come pre-soldered with a wire extension so that you don't damage it. So, overall, it looks like this, and we call it a strain gauge or a strain gauge cross set. So, how it works? It works very, very simple. What it says, a basic theory behind this is change in resistance per unit. Resistance is now proportional to the strain which acts on it. So, there is a constant of proportionality for this that is known as a gauge factor. If you talk about the gauge factor, it is a change in resistance by the total resistance of this gauge. So that is a constant anyway. So this is the strain which is acting. So, the gauge factor is defined like this. So normally, when we buy such strain gauge cross set, they specify what is the gauge resistance for this and how much is the gauge factor. Normally, it ranges from 0 to 2 gauge factors that are available in the market.

So, how it is mounted, how it works, is very, very simple. So, you may have a typical beam which is there, You can put your strain gauge sensor here somewhere over here, and you have a fixed beam. Let us say it is a cantilever that I am trying to draw. So if it bends like this, you are having a force which is acting from here, so it will bend it like this. It will bend it like this. So what will happen? This strain gauge raw set, which is fixed on top of the beam, will see some kind of extension. It will be extended if it is put with an adhesive on top of that. So what it will do effectively is it will try to bend that beam. This force will try to bend this beam, and, yes, you will see some extension in this, and that will change the resistance of this kind of wire. So, extension normally will increase the resistance, whereas if it is compressed, if this strain gauge raw set is fitted somewhere over here at the bottom side of it, it will see compression. So, if you compress to reduce the length of this, it is reduced and effectively that will reduce the resistance. So, this change in resistance is now used as a factor to detect any change which is acting on this beam. So this force is causing strain, this force is causing strain. So, it can be tuned to detect precisely the force or the strain.



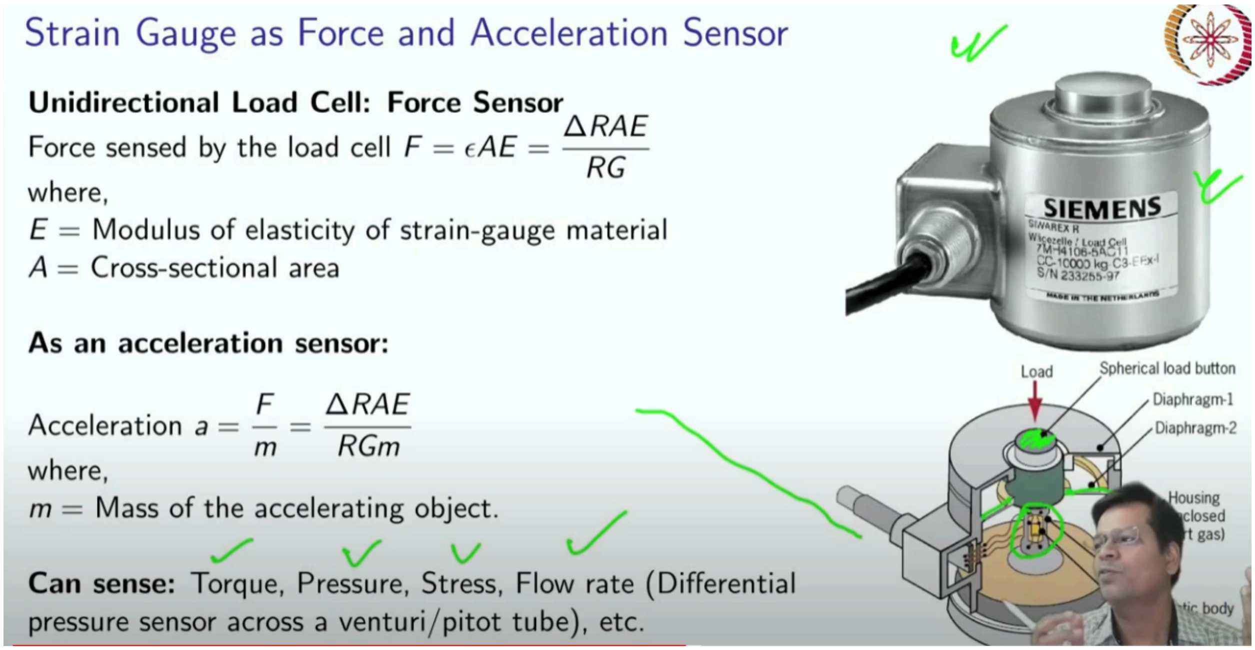
Also, If you remember your strain formula, strain can be simply written like this: so the modulus of elasticity is equal to stress upon strain. So, stress is force per unit area, and strain is strain.

$$E = \text{stress/strain}$$

$$E = \frac{F/A}{\varepsilon}$$

$$G = \frac{\Delta R/R}{\varepsilon}$$

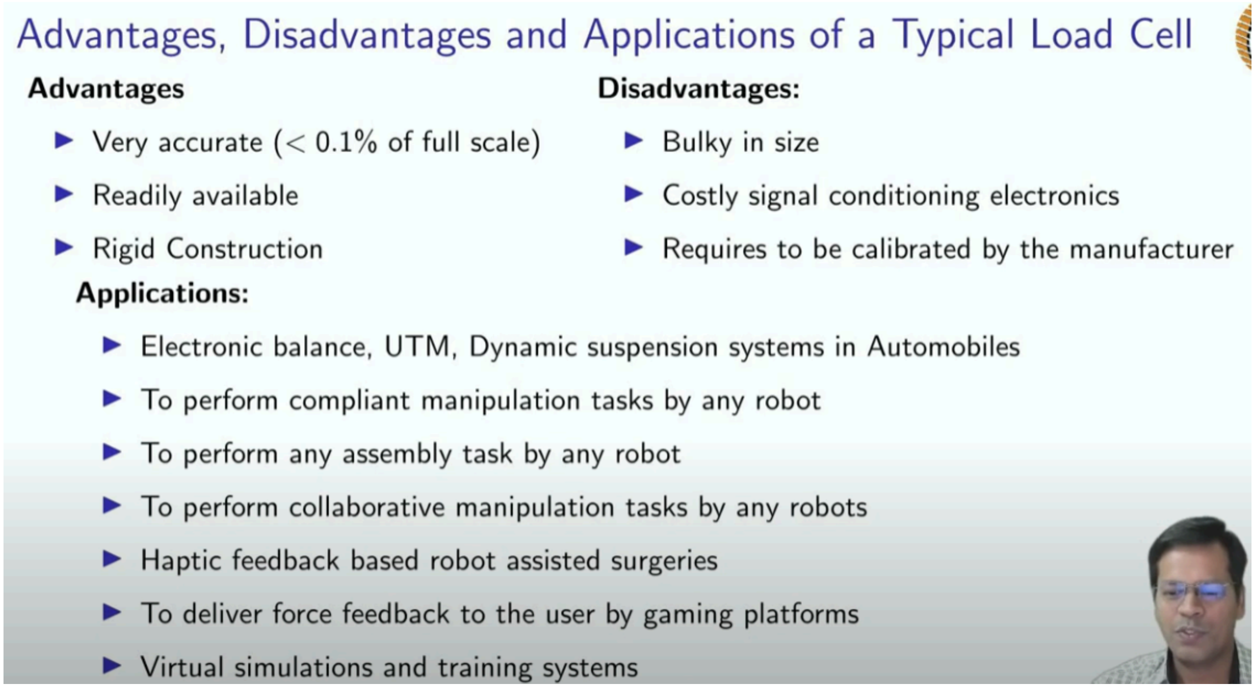
So, you can call it that modulus of elasticity. Now, if you simply rearrange this, it can be written like this: So, what was your gauge factor? Gauge factor was a change in resistance per unit, resistance by strain. So you just substitute this strain here in this equation. What do you get? You get this. So, this is your typical force which can be sensed by this kind of load cell. So, you can detect force. Normally, once the beam is made, that cross-section area is not going to change. OK, Young's modulus of the material is not going to change. Gauge factor: once the strain gauge is lost, it is soothed, and it is put with an adhesive that is not going to change. The total resistance of the gauge does not change. So, what changes? Is force? A force which is changing, and what you see as an effect is a resistance that is changing. So, if you can detect a change in resistance, you can detect force.



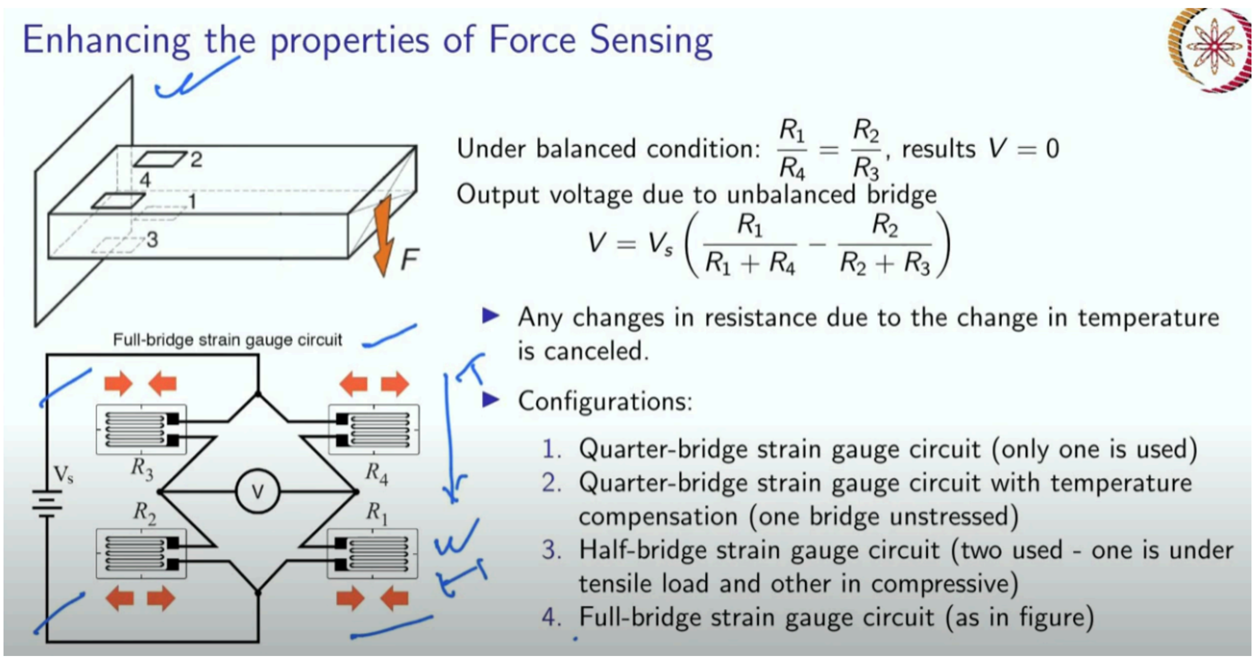
So this is how this can be used like a force sensor also. So, as an acceleration sensor. If you detect, if you can detect force, you can detect acceleration because acceleration depends on force. M is constant, and F is equal to m into a. m is a constant of proportionality here. So, acceleration can be detected by measuring the force also. We have learnt it earlier also.

$$F = ma$$

It can detect many other parameters. It can be mounted in a way where if there is any torsion in a beam, it can detect the change in resistance. You can mount this strain gauge rosette in such a way so that any torsion produces distortion in some kind of beam element, and that can be picked up by a change in resistance, which is happening in your strain gauge. So normally, it looks like this: This is a Siemens one, OK? So, inside it you see there is a small beam with a strain gauge rosette, which is fitted there. It has a very nice enclosure with a kind of diaphragm all over so that any water does not get in. So it is fixed within a strong housing so that whatever force it is supposed to check, it does not get damaged with that force itself. If it hits somewhere else, it should not get damaged. So, this is the place where the load is to be applied. And this is. There is a transmitting wire which can transmit that particular sense signal to a long distance. It can detect torque, and it can detect pressure, stress, and flow rate. So, is there any arrangement that can be made using this? So, you just need to have an arrangement where something that you are going to sense creates a distortion in this strain gauge and that will create the change in resistance that you can pick up.



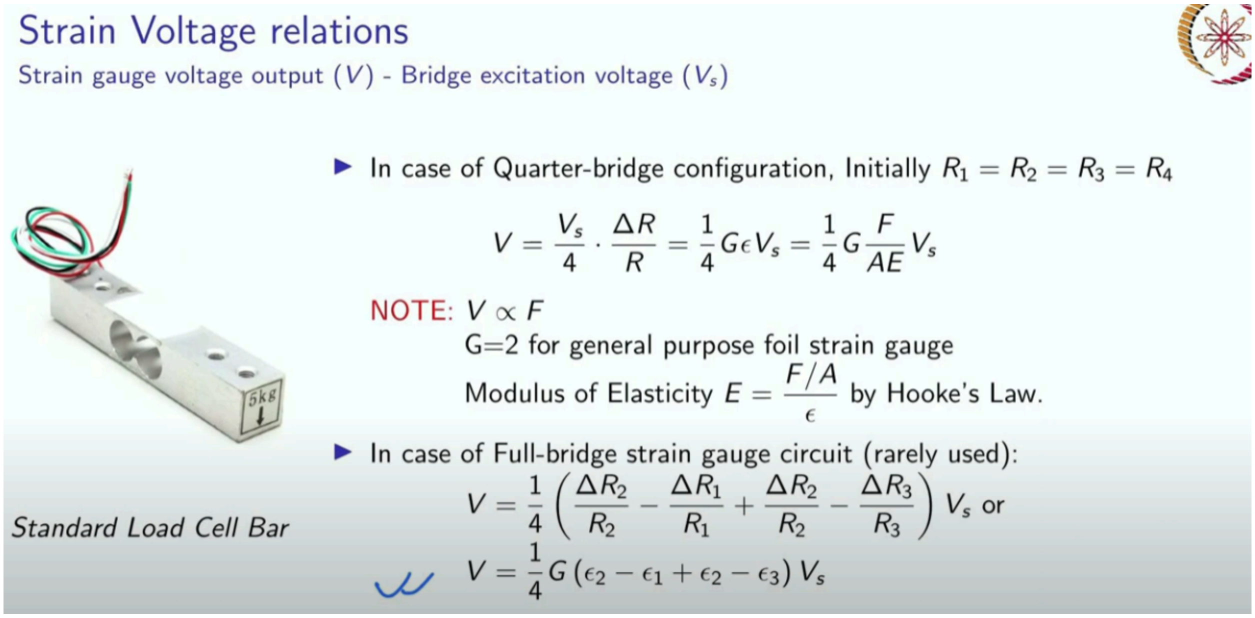
So, yes, moving, and so it is. They are very, very accurate: almost 0.1 percent of the full scale. Let us say it is designed to be used with 0 to 100 kg. Then, you should not see more than 1 kg of error. So, that is quite a big of an error, but, yes, it can be taken care of by having some other compensation mechanisms inside. These are readily available because they are just wire resistance. OK, So they are very inexpensive, and they are readily available. And the kind of enclosure, which is the way it is made. They are very, very rigid in construction. It has a beam with an adhesive which mounts this strain gauge sensor. So, once it is made, it hardly goes bad. It can see 10 to 15 years of life altogether. Yes, at times, you may require recalibration. That is the issue with this. So, yes, they are very bulky because of the way it is constructed- again, it has a beam which cannot be made very compact. So, they are bulky. Some conditioning circuits make your data transfer to a long distance to pick up this change in resistance. So, those conditioning circuits are there, which is a little costly but not very costly. Again, they require to be calibrated by the manufacturer when you buy it. So, they sometimes provide you with calibration certificates. So, that is very, very mandatory in the industry when you use it. So, even if you have seen this kind of thing, let me just switch to the applications. What this is. It is an electronic balance. You have seen this in the grocery store also. When it is used for that particular kind of balance. And the way they are handling it, it is very, very bad, and still it works, you see. So that is proving that theY are very, very rigid in construction Because it is calibrated, at least for your grocery shop owners. They hardly get their calibration done once they buy it. So, it may be very, very inaccurate that way, But in industry, when it is used, you have to go for recalibration because you want to work precisely. Your universal testing machine, which is there in your lab, may use this kind of sensor. Dynamic suspension system in your automobiles that changes its behaviour with the kind of road it sees, So, that also uses this to check the kind of force oscillation that suspension is seen. So, to perform compliant manipulation, a task force sensor is required At the wrist of the robot. Normally, it is fitted so that any object that it is handling it comes to know immediately whether you have closed your gripper. But yes, it did not pick up the object. So, you immediately will come to know if you are also checking the weight that is getting increased if you are holding that object. So, unco.Mpliant manipulation, that kind of assembly task if your robot is doing, maybe cooperative manipulation if it is doing. So, this kind of operation. They require this force sensor to be fitted, like grinding, polishing, and buffing, So all the surface contact where you require constant force is to be maintained, that is there. So, to perform any assembly task by any robot, this force is to be sensed. To perform collaborative manipulation, for performing surgery, to give feedback of force, force is to be sensed, OK, So that is why it is fitted. And to deliver a force feedback to a user who is playing a game, maybe. So, a virtual environment force. This type of system can be used to handle something in the virtual environment. You apply a force, and that force is sensed and transmitted to the virtual environment to handle something, or virtual simulation and training system, OK. So, this is how a force sensor is designed and it is used.



So, let us move ahead with a little higher variety of force sensors quickly. So now, similar cantilever, you can see you have almost 1, 2, 3 and 4 strain gauge rosettes. Why this is there, I tell you now. So, they are, and they are fitted like this, as shown in the figure. So, each of the beams of a Wheatstone bridge now has this strain gauge rosette. Why so many? So, let us talk about that. So, under the balanced condition of the Wheatstone bridge, you know, if R1 by R4, is equal to R2 by R3, the ratio is the same. You see, a zero voltage across these two terminals and no current flows through it, and V becomes equal to zero. This is the balanced case. So, output voltage, in the case of an unbalanced bridge, which appears over here, this voltage which appears here, Vs, is the source which is applied. So this resistance, if it is not balanced, will produce an output voltage which is given by this.

$$V = Vs\left(\frac{R1}{R1+R4} - \frac{R2}{R2+R3}\right)$$

Now, this simple physics can be used to detect forces. They can be used to detect force, change in resistance or many other parameters like strain if you want to check. So, why so?Many. So, any change in temperature will cause a change in resistance. If you at all have calibrated you the way you fitted it here earlier, so you just had one sensor. If you have calibrated to see 5 Newton to see a kind of force, so with temperature, if this resistance has changed, it maybe 5.5 Newton, which creates the same kind of change in resistance. So, that is not desirable, OK? So, once you have calibrated, it should be rough and tough, as if the temperature change and the surrounding change it is to be considered to design any such force sensor or strain gauge sensor to compensate against those temperature changes. So, this kind of arrangement is made. So let us just forget 4 of them. Maybe just 2 of them should be good enough to do it. How I will tell you in different ways. So yes, there are various configurations in which this kind of strain gauge is fitted. One can be just a Quarter-bridge. Quarter means 1, 2, 3, 4. One of them can be used to mount this, and others can be simple, a balanced resistance. If your resistance is strain gauge resistance, let us say if it is 20 ohms, fit 20 ohms to all 4 of them. All remaining 3 of three branches, OK? One of them can just be your strain gauge, and if Wheatstone is balanced, so if just one of them is changing, because that is the one which is mounted on the cantilever beam, if that is changing its resistance, that can be detected quickly by changing voltage, which appears here. So, that is. this configuration is known as a quarter bridge. But yes, this is sensitive to changes in temperature. So, if temperature varies, the behaviour of this voltage changes. So that is not desirable. So, there is another configuration which does most of the things for us. So, yes, quarter bridge circuit with just you don't have this. You have fixed resistance here. You have fixed resistance here. But two are there. One is your strain gauge, other one is a dummy one. This is just a dummy one. One of them is mounted on the cantilever beam, on this beam, but the other one is just in the same environment. It is kept so that any change in temperature will cause a similar change in this as well as this. So, the sensor sees the change, and this dummy strain gauge will also see a similar change. So, temperature change will not cause. The, let's say, balanced bridge has a component. R1 by R4 should be equal to R2 by R3. So this, anyway, will be constant because that is a constant resistance which is there. So, R4 is the dummy one, and this is your gauge one. This is your gauge. So if this sees a change by k times, this also will see k times change in its resistance value. So, ultimately, they get cancelled. So, any change which is caused because of temperature is linear in nature. So, they get cancelled. Ultimately, the balance status remains balanced. So R1 by R4 is still the same. So, whatever remaining change that you see in one of the branches R4 here, if it is not the dummy one. So, if this is changing, it is only changed because of the forces which are there or the strain which is happening. So this is completely taking care of the temperature change. So, this is a Quarter-bridge strain gauge circuit with temperature compensation. So, with just one bridge that remains unstressed. Two of them were constant, and one of them was used like a gauge. So, there is another good arrangement. Let me just vanish to make things very simple for you. So yes, this is a strain gauge circuit, a half-bridge strain gauge circuit. Two are used, and two of them are used. So, sometimes the forces which are acting from outside this may not be very huge enough, but you still want to see the change. So instead of changing just one branch of it, you can have two branches. You can use the top branch that you see in tensile loading, whereas the bottom one is in compressive loading. So one of them will extend, other one will get compressed. So, this is how. So one of them will extend in length, while the other one will just contract. So, the change in resistance will be twofold. One of them will see an increase in resistance, whereas this one will see a decrease in resistance. So effectively, this balance is stated status now, which is seen here. So, R1 by R4, two changes will be there. One will be, let us say if you have fitted two and three here as resistance, so both will change simultaneously. So, that will affect the resistance twofold, and your Wheatstone bridge will be unbalanced significantly, and this voltage variation will be maximum. So, that is the reason why one should use two strain gauges like a gauge. One of them is at the bottom side of the beam other one is at the top side of the beam. So, to enhance the amplification, you want to see more, so in that case, you can use it. So it requires four of them, two dummies and two as a strain gauge. So that is this, and then the final one is the full bridge strain gauge circuit, as shown in the figure. So yes, what do you see? This is in compression, and this is in extension. Compression and extension, that is because of tensile loading. So, this is how it can be mounted, the way it is shown in this figure. So that is full. This is rarely used. This is the way you can see the maximum change in the voltage. Because of the forces which are there, Things are very, very complex because any problem with even a single one of them can make things very bad. So because they are glued with an adhesive, they are prone to come out due to the loading which is there. So, this is a little uncertain here. That makes little unreliable. So, that is the reason it is hardly used until and unless it is dimly required, because forces may be very, very small. You see, it is automatically compensated by temperature changes because all four of them are equally affected by the temperature. So, these are the four different configurations which are there.



So, I will just quickly show you the formula and how it works. So, this is what a quarter bridge strain gauge configuration looks like. So, the voltage changes if you substitute the values here. You put the resistance. Few of them are constants. So if it is constant, you can put the same value to all these. If just one is changing, you put one rest. All are constant. So if you do that, you will see it comes out to be Vs by 4, delta, R by R, approximately.

$$V = \frac{Vs}{4} * \frac{\Delta R}{R}$$

So, this is there, and if you substitute your original formula for strain over here, you see this one.

$$V = \frac{1}{4} G \frac{F}{AE} Vs$$

So, voltage, which changes to force, can be formulated like this. So, the only thing which is changing here is the force, and you see it as a change in voltage that comes out of it. So this type of bar is normally available even in many online robotic shops for your projects if you want to use it. So you see, it has a strain gauge which is fitted here, fitted with external wires, which goes out, and it comes with a ready-made circuit which does amplification and transmission job for you. So, yes, this is a quarter bridge configuration, and you see, the voltage which is proportional to f, g is 2 gauge factor is normally 2 for this type of foil strain gauge for most of the available gauges. So, if it is not known, you can take it as 2.

$$V \propto F$$

Modulus of elasticity: this is a well-known formula. You know it already.

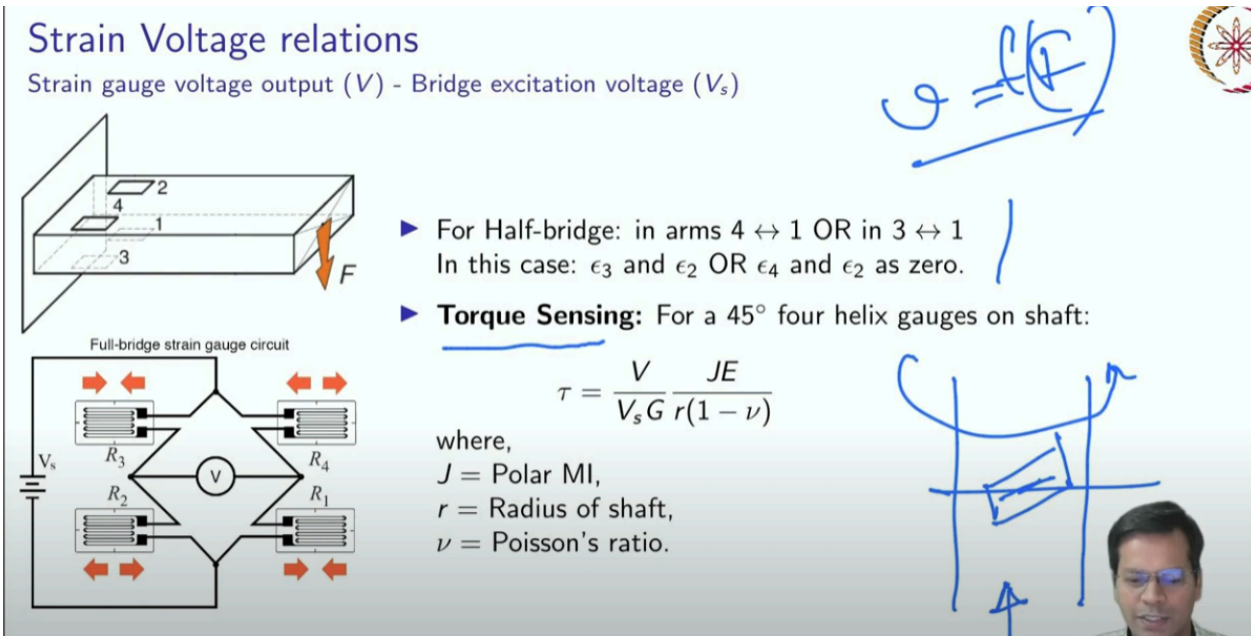
$$E = \frac{F/A}{\boldsymbol{\varepsilon}}$$

So, if it is a full bridge circuit, this is the case. So, changes in resistance per unit resistance for different resistances are here. This is how it will look like, and in terms of strain, it is written like this.

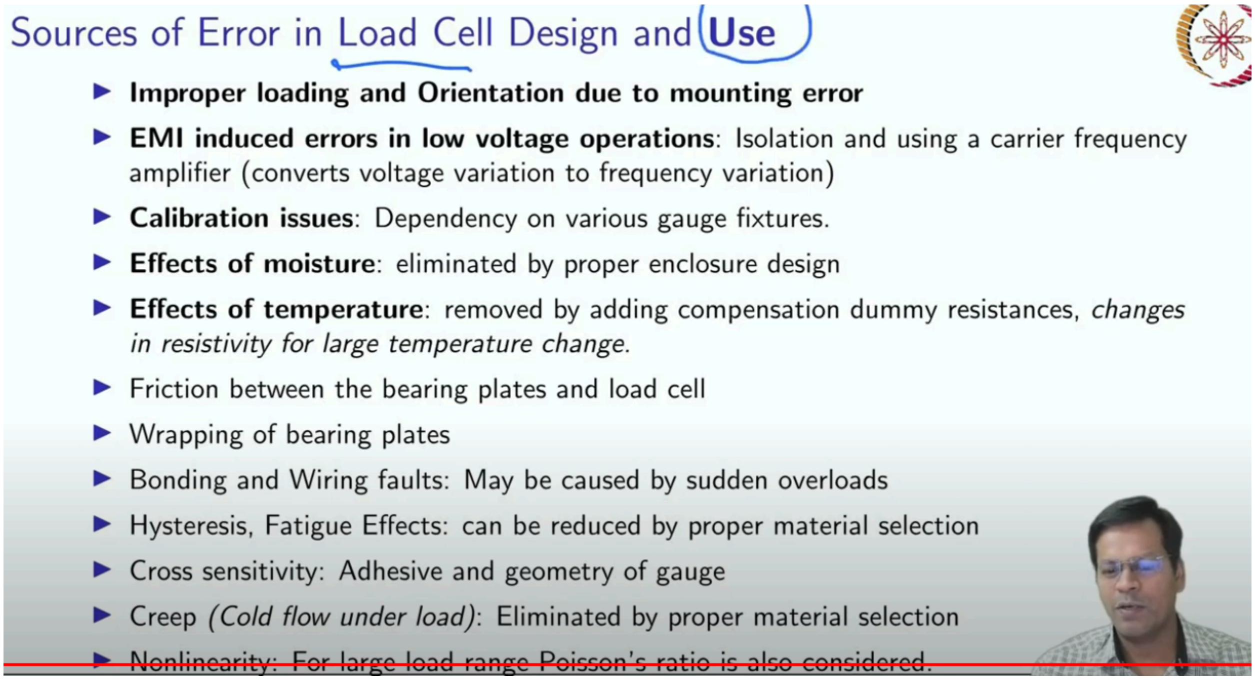
$$V = \frac{1}{4}\left(\frac{\Delta R2}{R2} - \frac{\Delta R1}{R1} + \frac{\Delta R2}{R2} - \frac{\Delta R3}{R3}\right)Vs \text{ or}$$

$$V = \frac{1}{4}G(\boldsymbol{\varepsilon}_2-\boldsymbol{\varepsilon}_1+\boldsymbol{\varepsilon}_2-\boldsymbol{\varepsilon}_3)Vs$$

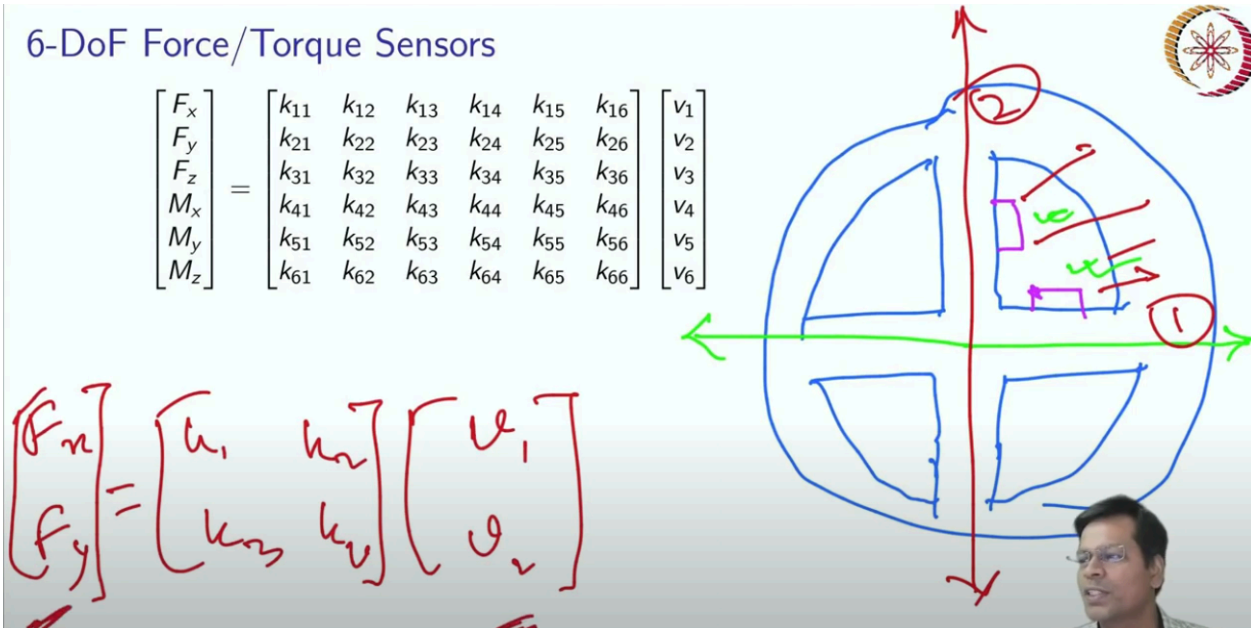
I would not get into the derivation part of it much because this is beyond the scope also, but yes, it can be readily used. If you are from industry, if you are a project student, maybe in research.



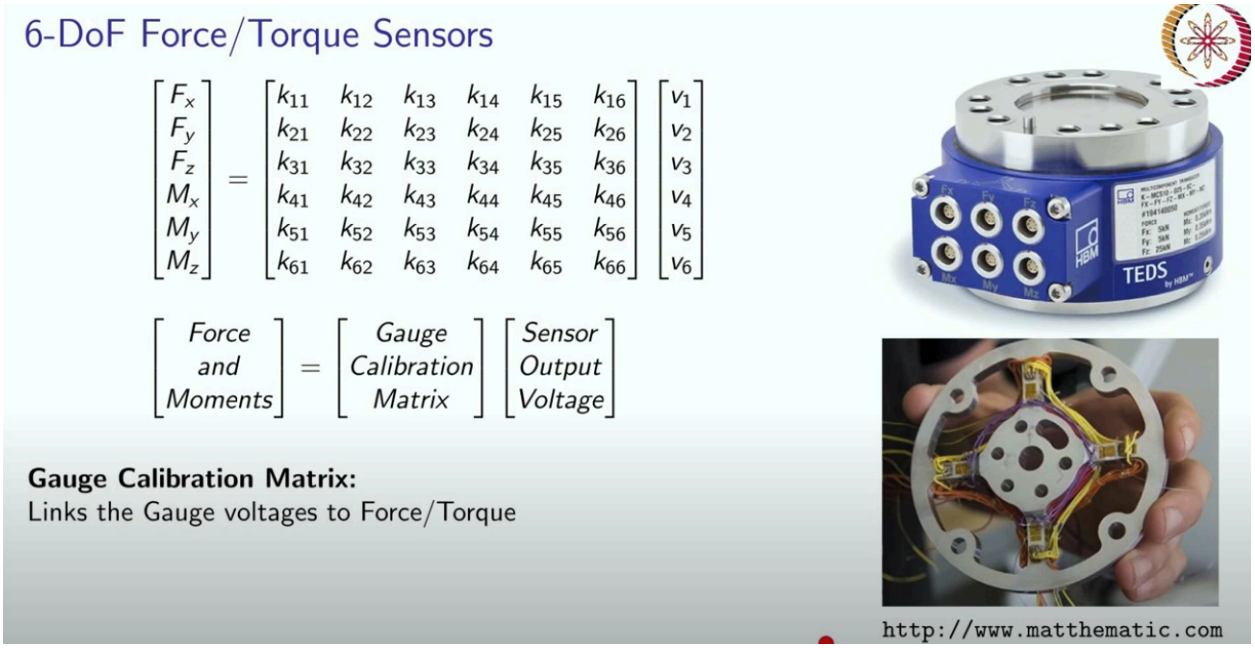
For half bridge system, for configurations which are here. So, you can have in 4 or 1 or 3 or 1, you can put your strain gauge. In that case, this and this or this turns out to be 0. In that case, you just substitute them. You will get the end formula for output voltage in terms of the applied force so that, as a function of force, you can get it. So, yes, this can be used as a torque sensor so that you can have a beam. You can have a beam where your strain gauge Dorset is fitted like this at different places on the torsional beam. So, this can detect the torque so it can see the change in torque. So, yes, it can also see the force if it comes from here. So this is any change in torque will cause a change in this as well, as a change in force can also be picked up. So, if it is just mounted like this, it can just detect the torque. So, if it is fitted like this, it can just detect the torque. There is some linking between the force and torque. We will see it later in other slides.



So yes, there are many sources of error in this kind of load cell design, commonly known as a load cell, not like a force sensor and use also. While using, you have to be more careful because most of the time, you buy such force sensors. Normally, you do not design this kind of sensor, so forget about the rest of the things. This is very, very important. If someone is very interested, they can go through this also. But, yes, improper loading if you believe that your force is going to come from this direction. Your force cell should load cell should be mounted like this. If it is inclined, even by a degree, it will give you an incorrect reading, and if at all you still want to go ahead with that, you go for recalibration of that. So, orientation errors in mounting can give you improper results. So, any electromagnetic induction nearby, because you know it is a kind of circuit which is there inside, so they are prone to get affected by any external electromagnetic signal. So, this would be kept very well apart. Normally, the kind of sensor I showed you which was an industrial sensor, so it was protected from all around using a metallic casing so that it does not get affected by EMI. So, isolation and using a carrier frequency as an amplifier are a better way to use it. But that also is taken care of by the manufacturer of this kind of force sensor. So, that is there. Calibration issues are there because, over a period of time, your beam changes its behaviour, and the kind of adhesive that changes its behaviour may be. The strain gauge also has changed, so it requires calibration, maybe every year or two years. You have to go for it. So, yes, the calibration issue is there, and dependency on various gauge fixtures is always there. OK, the way it is fitted, so you have to go for, even if it is mounted somewhere, that mounting is to be checked sometimes. So, yes, the effect of temperature, you see, but that can be easily taken care of by fitting a dummy. Resistance, you know, but yes, by a huge lot of change if it is there in temperature. So resistivity is changing, not the resistance is just which is changing, which is getting cancelled out. So, the large temperature change effect should be taken care of. OK, so there are many others which are listed here. I would not get into this. But yes, you can simply go through this if you are interested. But in industry, normally we see these kinds of errors which should be taken care of.



Now, just look at how 6 degrees of freedom force sensors are designed and used. So, yes, you have different. Let us just give you an example. Let us say you have a beam which is like this: Now, you are not just fitting a strain gauge in one of them. This is your beam. This is your design of the beam. So, you may be fitting your strain gauge here. You are also fitting a strain gauge here. So, in this case, what will happen? At least any application of force in this direction will be picked up by these two. This is mostly this one a bit also will change. OK, so any change in force in this will change both of them. Any change in force along this direction will also change these two strain gauge voltages. OK, so it will give you some change in this and this also. So this time, this will change more, and this will change less. OK, so you got it. What I am trying to say is: so this can be arranged like so voltage to the two voltages which are coming out of each. Let us say: this is one, this is two, so this is one, this is two, so two voltages can be linked with constants like k1, k2, k3 and k4 to give you a force along x and force along y.



So, this is a simple relation which can give you the forces that are appearing on those branches. So, basically, this is, six different gauges are fitted. So this is for six degrees of freedom load cell where you have three branches, and in those branches, you have three load cells which are fitted in, that is, to detect force, and three for the moments. OK, so, and then it can be related like this: it can detect moments along all three axes and forces along all the three axes, but anything which is appearing, any external force or moment which is appearing, changing all the voltages, not just one of them. So, that is the reason you have a matrix-this is known as a gauge calibration matrix-which is provided by this kind of load cell manufacturer. Six degrees of freedom cell manufacturer.

So, yes, they are made like this, and you see, this is a load cell made by TEDS. So, these voltages appear here. All six are arranged here, and they can be transmitted, and you have this gauge calibration matrix, which is provided by the manufacturer. Simply have this voltage array over here, this matrix over here, and you can calculate your force and the moment which is appearing. These kinds of sensors are mounted on top of the rest of your robot so that you can see the forces and moments. So, the gauge calibration matrix is to be recalibrated every maybe one year, as prescribed by the manufacturer, and then it can be used very precisely to do any compliant manipulation assembly, just like your task, like surface finishing task and this kind of task.

So, that is all for four sensors and proximity sensors and sensors altogether. We will discuss. So, this is just a representative picture which is there. I have taken it from here. You can just look at it. So yes, finishing this. So, in the next class we will see some leftover portion, that is, a limit switch and classification and characterisation of this kind of sensors, any sensors. So, it needs to be classified. So, that you can select the proper one of them if you want to use characterisation.

That is the most important part of the next class. That is what all parameters are listed in a datasheet, if at all you find one such sensor. So, we will talk about all of those in the next class. That's all. Thanks for today.