Wheeled Mobile Robots
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Lecture - 4.2
Sensors and Sensing

Hello welcome back. So, in the last class, we discussed about the Importance of Sensors and Sensing and how this can actually be used for giving a perception of the environment to the robots.

We saw that most of the autonomous robot or all the autonomous robots need to have a capability of perception of its environment and without this perception, the robot will not be able to do any of its task. And sensors play a major role in collecting information and then, this processing of this information helps the robot to have a clear perception of its environment.

So, today let us look at the sensors; some of the important sensors that are used in mobile robotics and how these sensors are being used in order to collect information from the surroundings and under various situations ok.

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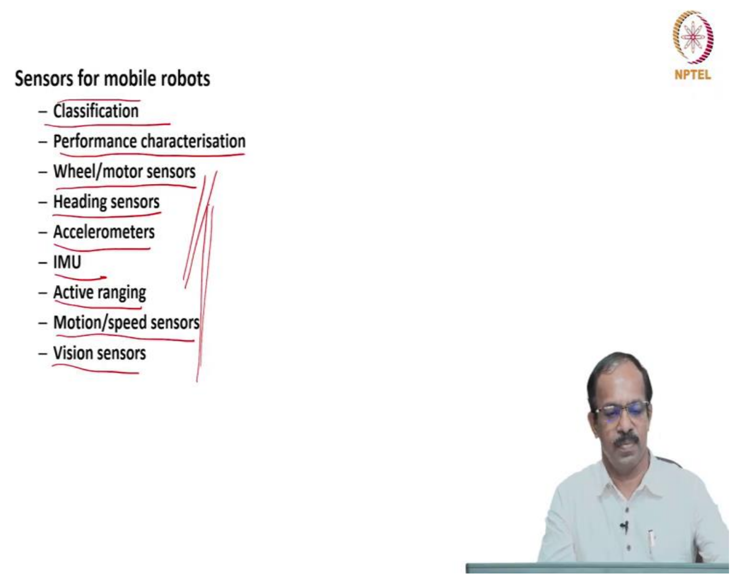

So, when we talk about sensors for mobile robots, we will be looking at the classification of sensors. So, how the sensors can be classified; there are different type of sensors, so we can actually classify them under different categories. So, we look into the that one, how do we classify them and then, we look at some of those performance characterisation of the sensors because sensors need to have some performance characteristics. So, we will see what are those important characteristic that we need to understand.

Then, we look at some of those sensors which are commonly used in mobile robots ok. So, some of them are for the environment, some of them are for the robot itself, I mean for its own information. So, we will talk about the wheel and motor sensors of the robot; then, the heading sensors, accelerometers, inertial measurement unit, then ranging sensors, active ranging sensors, then the motion and speed sensors and then we look into the vision sensors also.

Since some of these sensors are already familiar to you, I will not be going into the details of each and every sensor. I will tell you the basic principle and then, how this is how these sensors are used for getting information from the surroundings. So, that is going to be the discussion in this class ok.

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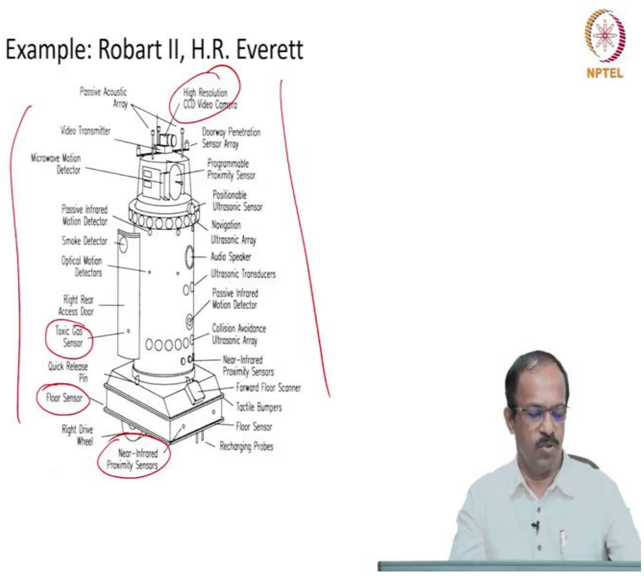

This actually shows some of the robots with different kinds of sensors. So, you can see a large number of sensors may be needed in mobile robots that may include the cameras or it may include the proximity sensors, then floor sensor etcetera etcetera. So, there can be different ways of looking at the problem. So, some cases depending on the use of the robot, you can have some kind of toxic gas detector also.

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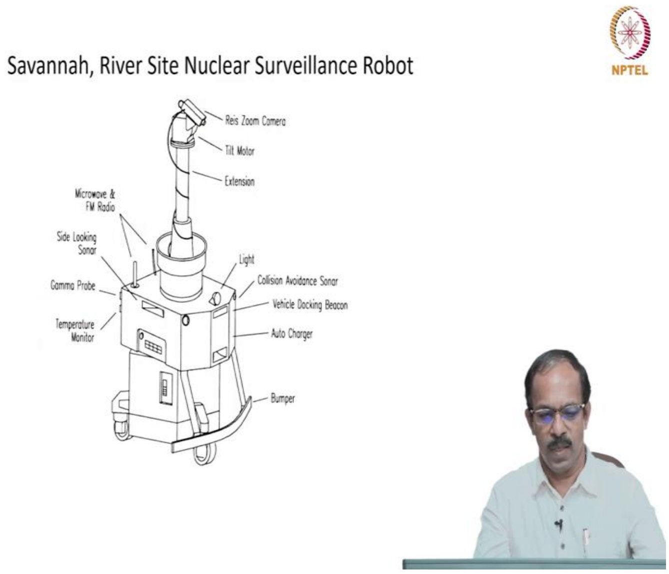

So, that depends on the application of the robot. Again, this is another example for mobile robot with various kinds of sensors ok.

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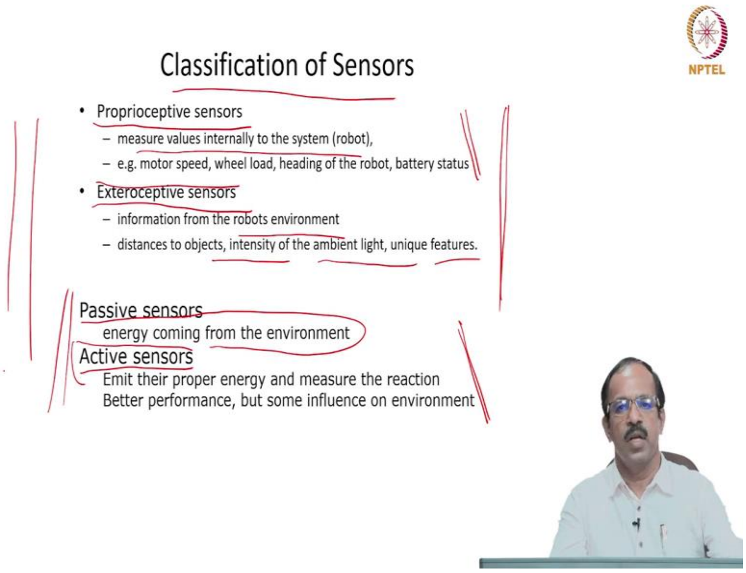

So, let us talk about the classification of sensors. When we classify them, we classify them into primarily into two categories; one is to get the information from the robot itself; from within the robot, we want to get some information. For example, the wheel speed is an information of the robots, temperature inside is an information about the robot or the what is the velocity at which the robot is moving. Again, it is an information from the robot. But there are some other information, we want to collect from outside. What is the is there an obstacle on the path or what is the temperature outside or what is the humidity outside? So, there are many things which we can get from outside also.

So, we can classify them into two categories; one is for internal information, one is for external information. So, we classify them into two categories; one we call this proprioceptive in sensors, the other one is exteroceptive sensors. So, these are the two kinds of or two categories of sensors that we can have or two classifications. So, the proprioceptive, they measure the values internally to the system that is; motor speed, wheel speed, heading of the robot, battery status etcetera.

So, this is basically the proprioceptive sensors and the other one, exteroceptive sensors basically information from the robots environment; distances to objects, intensity of the ambient light, unique features etcetera.

So, that is coming from the environment. So, sometimes the same sensor can be used for both applications also. There are various combinations possible because sometime the again depending on the robot, you may require some information from outside the environment, outside the robot, some maybe from inside the robot.

So, whichever sensor is used for measuring the internal values, we call them as proprioceptive and whatever is used for outside information is known as exteroceptive sensors. And another way to classify them the sensors is basically through based on the energy, that is passive sensors and active sensors. So, in passive sensors, the energy is coming from the environment. So, the robot does not have any; sorry, the sensor does not have any energy source.

The energy is coming from the environment. In the other case, the active sensors the sensor emit their energy and then use that one to collect the information. So, this that the difference between these two are one is emitting an energy and then, using that to collect the information; the other one is just getting the energy from the environment and use that one for collecting the information. So, we will see some examples.

For example, if you have range sensor, a laser range sensor. A laser range sensor will send a laser signal and use that signal that energy to get the that reflection and then, use that one for measuring the distance. So, that is actually an active sensor. So, some sensors will emit energy some will not emit.

So, the thus which one has got its own energy and emit energy is called active, the other one is known as passive sensor. So, these are the two important classifications; one based on the application or how it where it is used and for what purpose it is used, another one is whether it is has got an energy or not, its own energy or not used for sensing right.

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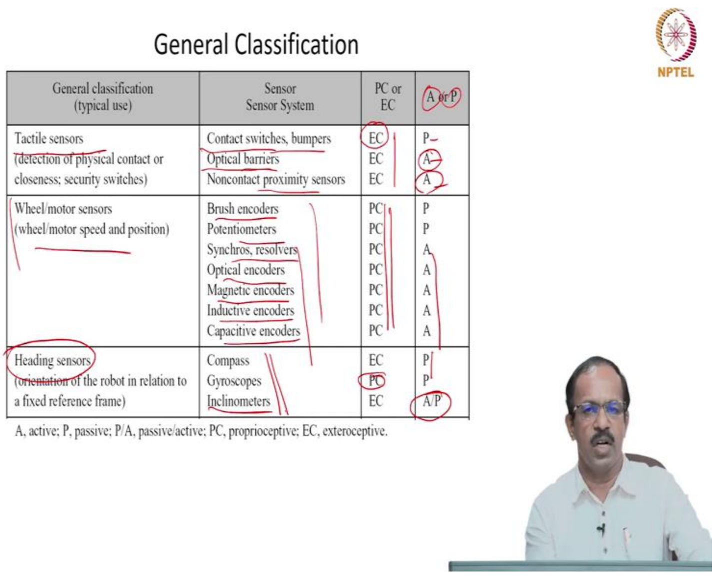

So, EC or PC, you can check whether it is an exteroceptive sensor or a proprioceptive sensor and active or passive. So, you can see whether it is active or passive.

So, for example, tactile sensor. A tactile sensor used to find out the contact; physical contact or how close it is to a obstacle or an object that is basically the tactile sensor or a proximity sensor. So, they are contact switches, bumpers, optical barriers etcetera etcetera. So, they are all exteroceptive because they are used to identify the environmental parameters or environmental data is collected using this one and some of them are passive, some of them are active.

So, for example, contact switch, it is actually a passive one because there is no energy is emitted something touches it, then it will give a signal. So, it is actually the external source itself is giving a information to it without giving any giving out any energy. But the optical barriers provide an optical signal and whenever there is a break of that signal that is used for measurement; so then it is a an active one. Similarly, non contact proximity sensor, they will actually emit some signals and based on that signal only you will get so its again active sensor.

And coming to the wheel or motor sensors, so mobile robot as you know we in the kinematics, you might have studied that we need to understand at what speed the wheels are rotating and if you know this wheel speed and the radius of the wheel, we will be able to calculate how much the robot has traveled and that can be used to identify the position of the robot.

So, that way, we will use many wheel encoders in order to get the wheel motor speed and position. So, we have many things like brush encoder, potentiometers, synchros, resolvers, optical encoders, magnetic, inductive, capacitive, there are many encoders. So, some of them are active. So, these are all active, but potentiometer is not an active one because it actually depends on the environmental input for its sensing. And these are all proprioceptive because these are all used for the internal information of the robot. So, it is a proprioceptive sensor.

Similarly, heading sensor, heading is basically the orientation of the robot. How much it is oriented with respect to a coordinate frame that is basically known as the heading. So, that can actually be obtained through compass, gyroscope or inclinometers and see gyroscope is a PC that is for the internal information. But compass is basically uses external magnetic field information and then, tells you what is the magnetic field and based on that, you actually decide what is the heading of the robot.

So, these are passive and this is it can be an active or a passive one. So, inclinometers can be either active or passive, depending on the principle used for designing the inclinometer. So, like this, we can see there are many sensors normally used in mobile robots. It can be classified into EC PC or active or passive sensors. We will go through some of the sensors, but not all the sensors we will be discussing.

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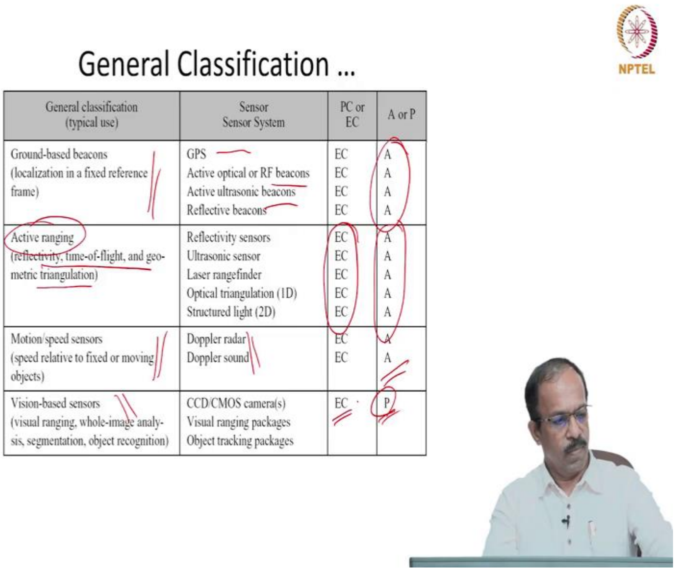

Again, you can see the localization that the GPS, beacons, they are all active ok. Then, you have this ranging; ranging is basically finding out the distance to obstacles in the surroundings. So, you can actually use various principles; time-of-flight, geometric triangulation etcetera and they are all active because they are all emit energy in order to get the information.

And again, they are all for external information, so it is easy. And the motion or speed sensors like doppler radar and doppler sound, again active. And the cameras, so basically passive. So, it will not emit the energy, but the light energy falls onto the camera. So, it actually gives a signal. So, that is why it is a passive one; camera is a passive sensor and it is an EC type ok.

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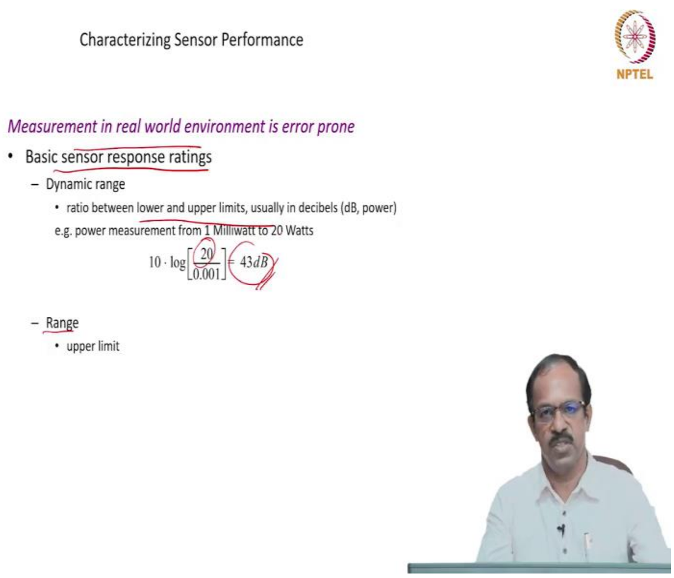

Let us now look at; so, those were some of the sensors and then, the we saw the classification. Before we discuss about the about the few sensors and their working principle, let us look at the character characteristics of these sensors.

So, based on the sensor performance, we can identify many characteristics. So, one is basically the sensor response. The sensor response the one parameter is the dynamic range. So, the dynamic range is the ratio between the lower and upper limits, usually in decibels. So, that is basically known as the dynamic range of a sensor.

So, what is the range that the sensor can measure? So, that is the I mean the range of values between which it can measure. So, you can see which is between 0.001 to 20 can be measured, then we call this as a 43 dB range, the dynamic range.

$$10 \cdot \log\left[\frac{20}{0.001}\right] = 43dB$$

And the normal range is basically the upper limit of measurement that is basically known as range. In this case, it will be 20. You can see this 1 milli Watt to 20 Watt will be 43 dB, but that is range is now if it simply asked this is 20 Watt is the range of measurement. So, the dynamic range is measured in decibels.

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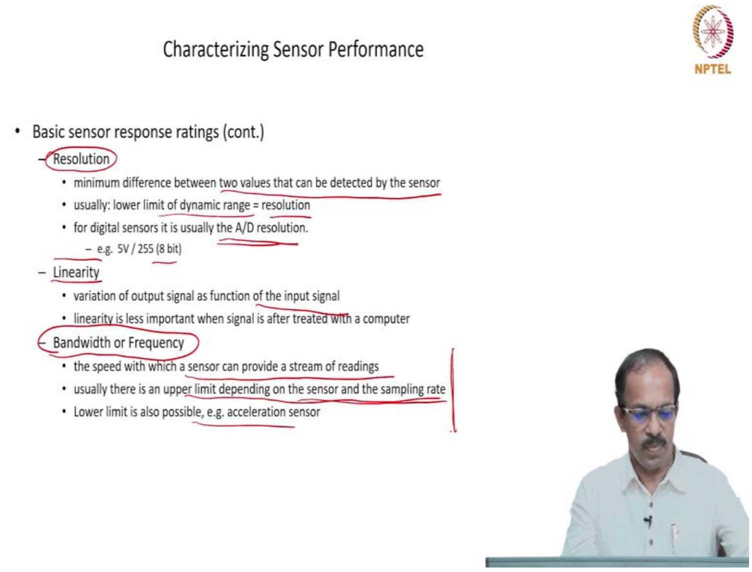

And then, we have the something called resolution. So, resolution is the minimum difference between two values that can be detected by the sensor. Of course, these are not specific to mobile robots; but since we are discussing about the sensors used in mobile robots, I just need to tell you all this. Because if you choose a sensor which is not matching with the requirements of sensing in that particular environment, you may end up with erroneous data or useless data.

So, we need to know a little bit about the response ratings also ok. So, the lower limit of dynamic range is the resolution. So, its 0.001, we normally we call that as the resolution ok. For it is usually the analog to digital resolution in the case of digital sensors. See 8 bit or 12 bit like that we tell, so that is basically the analog to digital resolution.

Linearity is very important; the variation of output signal as a function of the input signal. If the variation is linear, then we have its linear measurement; but if it is not linear, then we need to know what is the relationship in order to get the output from the sensor. One important characteristic is the bandwidth or the frequency of the sensor. This tell you tells you that at what speed, you will be able to collect the information and if that is that is sufficient for your application.

The speed with which a sensor can provide a stream of readings is known as the bandwidth ok. Usually, there is an upper limit depending on the sensor and the sampling rate. So, many times you will say it can use 100 Hertz; that means, you can have 100 cycles/second, we can have the data collection or the variation can be 100 cycles/second for that particular signal. Still the sensor will be able to catch the information; but if it is the signal variation is much more than that, then you want the sensor will not be able to pick up the data ok.

So, normally we will be having an upper limit for the bandwidth. So, normally we talk about it can up to 40 Hertz, 100 Hertz like that. But for the case of acceleration sensor, we will put a lower limit also; beyond that, less than that the robot sensor will not be able to pick up the information.

So, this bandwidth is an important one. Then, we need to know how the signal is varying, if the signal variation is if the if we know the frequency at which the signal to be measured is varying, then the sensor need to have a bandwidth which is matching with the signal that is being measured ok.

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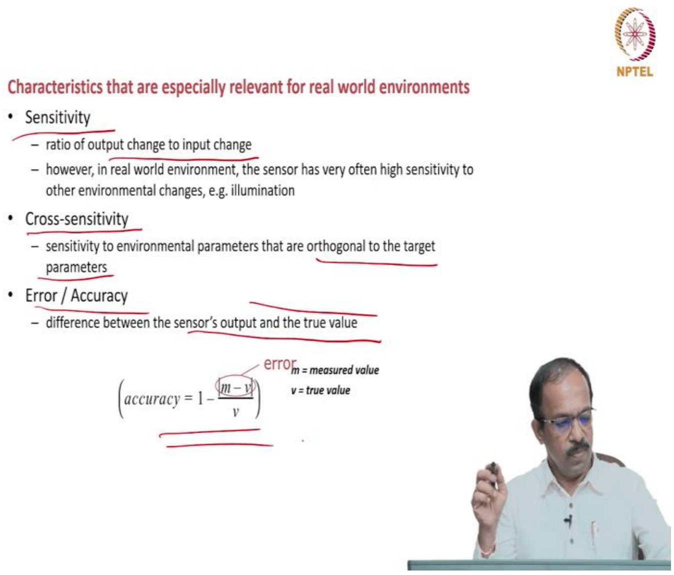

Another one is the sensitivity; the ratio of output change to the input change which is straight forward. But cross sensitivity is more important the sensitivity to environmental parameters that are orthogonal to the target parameters. So, you are trying to measure something, but if the sensor is responding to some other signal which is orthogonal to the measured signal, then we call this as a cross sensitivity. So, the cross sensitivity should be very minimal for sensor sensors. So, that will get the correct measurement of the data.

And then, error and accuracy; so the difference between sensors output and the true value is basically known as the error and $\text{accuracy} = 1 - \frac{|m-v|}{v}$. So, that is basically how you define the accuracy of a sensor. So, error is just the measured value, minus true value is the error; but $\text{accuracy} = 1 - \frac{error}{true\ value}$ ok.

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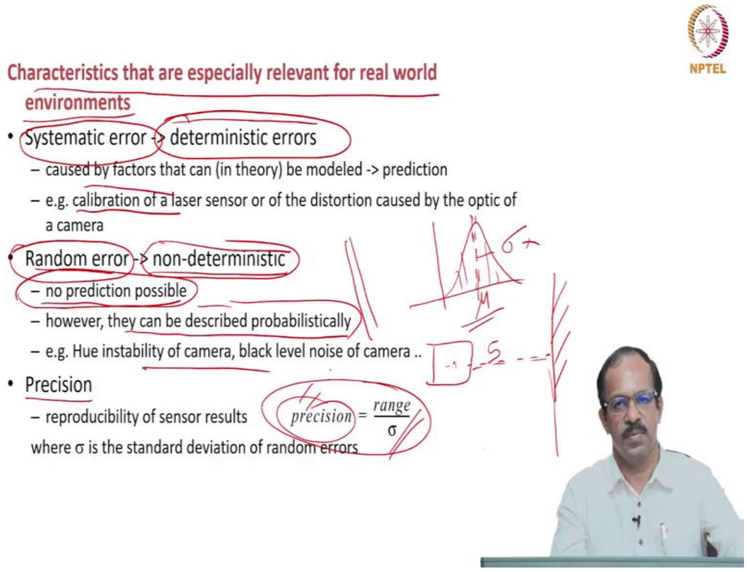

So, this is more important for the mobile robots because these are the characteristics which are very relevant to our real world situations. Most of the time when you take a measurement, there will be errors and these errors can actually be classified into two types of errors; one is known as the systematic error, the other one is known as the random error. So, what is the systematic error? That, I am trying to measure a distance, so I am having a wall here and I am using a sensor to measure the distance from here to here, I am trying to measure the distance.

Now, if I use the sensor, I am making 10 measurements, I will be getting 10 readings. So, we do not know depending on the sensor and the situation, you may be getting various values.

But this error some of the errors are very systematic or we call it as deterministic that is it is because of the calibration of the sensor or we did not calibrate it properly or there was some error in the settings that actually led to the error in the measurement and such measurements can actually be such errors can actually be controlled or we can actually compensate it by properly doing a calibration of the sensor. So, such errors are known as the deterministic errors which can be modeled and which can be corrected.

So, we call this as the deterministic errors and the calibration of that will actually avoid these errors. So, that is something which cannot avoid completely; but we will be able to calibrate the sensor over a period of time and if you use the sensor over a period of time, you will see that it degrades and then, you do a recalibration, then the sensor will be again working perfectly fine and the error will be less or the accuracy can be increased. But there are some other errors which we called as random errors or they call it as non deterministic errors. So, it is very difficult to predict these errors.

We do not know why it is happening; maybe many things are there, maybe the environment it is affecting, the temperature is affecting, humidity is affecting, the performance, we do not know and such errors are known as non deterministic error, which cannot be really overcome by calibration or anything ok.

So, no prediction is possible for such measurement such errors. So, if I make if I get 10 make 10 measurements and I get 10 readings. After calibration, I can actually bring down the variations to some level. But then, still I will see there are some errors still existing which I do not know how to controlling.

Because there is no way to it is not a calibration error, it is not a deterministic one; it is known as random errors which cannot be avoided. So, if no prediction is possible for such sensors, so you cannot really predict the errors and they can be only described using probabilistic methods ok.

So, we need to go for some probabilistic estimate of the error and that will give only a probability only, the type of error that can be that may be existing. So, this is one of the major challenges in using sensors in mobile robots. Because I am using the sensor to measure the distance and if I make 5 measure 5 readings and if I get 5 measurements, how the robot can actually decide which one is correct or on what basis the robot will take a decision?

So, I can only say that if I take my 5 measurements, I will be able to get a distribution like this. The mean value; see the mean value will be somewhere here, I can say and then, I can say oh this is the standard deviation that you can find. That much only we can model using probabilistic method, but we do not have any real value mu. So, because the distance what is measured can be here or it can be this or it can be, anything can be there; but we can only say that in a probabilistic way, we can say the mean value is mean is this and the standard deviation is this and most of the sensors that we use comes up with this problem.

So, there will be always a non deterministic error in the sensors and this actually makes the life of a robotic engineer very miserable because these uncertainties cannot be really overcome by the design and it has to be addressed through other methods only. So, this is one big challenge in using the sensors for perception process. We will see how this can actually be addressed as we move forward. So, the precision is basically defined as the range by sigma $precision = \frac{range}{\sigma}$ ok; so reproducibility of sensor results.

So, if you have a sensor which actually gives you too many readings, then we can only say that what is the precision of the instrument. So, the precision of instrument will be the $\frac{range}{\sigma}$. So, what is the range that it can measure and what is the standard deviation that will give you how precise is the sensor that much only we will be able to tell ok.

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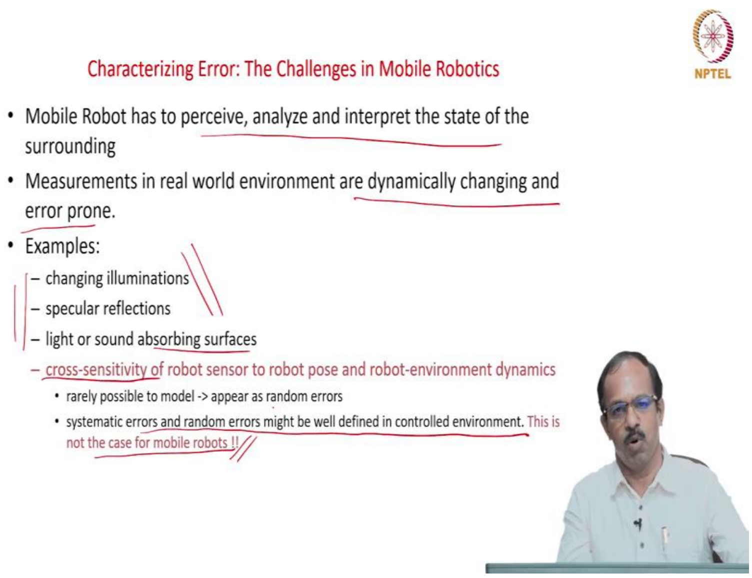

So, I just mentioned about some of those sensors and the performance characteristics. So, let us see what are the main challenges; when we use these robots for perception. So, as we know that we are using it for perception. So, when the robot has to perceive and analyze it, interpret the state of the surrounding. Measurements in real world environment are dynamically changing and error prone. So, all these readings are error prone.

So, whatever the sensor we use, you know sensor is 100 percent correct. The sensors will be having their own errors. So, how do we actually take these errors into account, while doing the perception process ok. So, the changing illuminations reflections and if you are having some light absorbing or sound absorbing surfaces, all this will lead to errors in the measurement.

So, it is very difficult to predict what will be the measurement because again, any changes in these factors will cause a error and then, as I mentioned the cross sensitivity is a big issue ok. So, it is very it appears as a random error.

And systematic errors and random errors might be well defined in controlled environment, but this is not the case for mobile robots. Because in a controlled environment, we can model it as a I mean even the random noise can be modeled well; but in the case of mobile robot, we are doing environment which is completely unstructured. It is very difficult to do this in the process ok. So, that is what actually the problem is.

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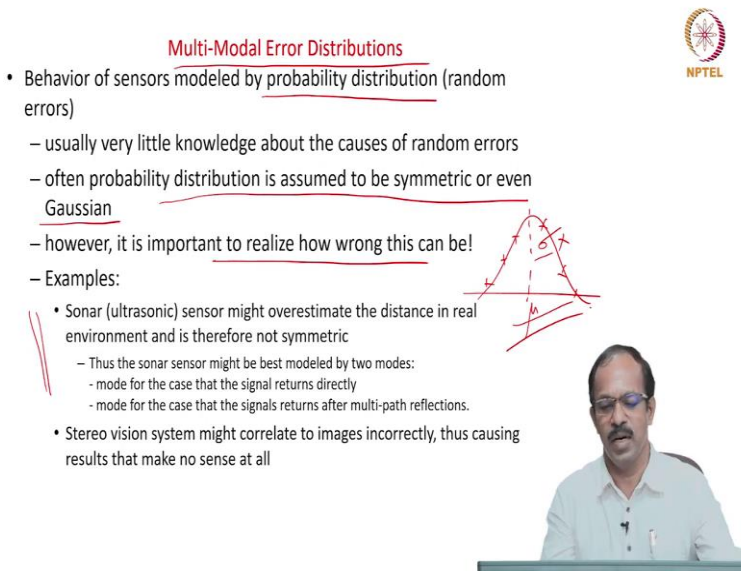

And how do we actually overcome this? We go for multi modal error distributions ok. So, this random arrays as I mentioned, it is very difficult to predict. So, what we do? We do the distribution. So, we actually predict them as random distributions or we will predict them as probability distributions and then, what we do?

The probability distribution is assumed to be symmetric or even Gaussian. So, Gaussian is the white noise distribution, where we can have the mean and standard deviation, the standard representations. So, we can actually predict it as ok, this is the way how the random errors are. Need not be always, but we will just say that ok, so we have a μ and we have a σ.

So, I can actually find out the I can distribute describe this by a probability density function. So, that is basically how we model the error. But you know this can be wrong ok. So, it need not be always correct. There can be lot of errors in that one. So, those errors will not be really taken care of and you make such an assumption. So, this is where we need to go for multi modal distributions or we need to go for multi sensor data fusion in order to overcome such errors in the even in the distribution models.

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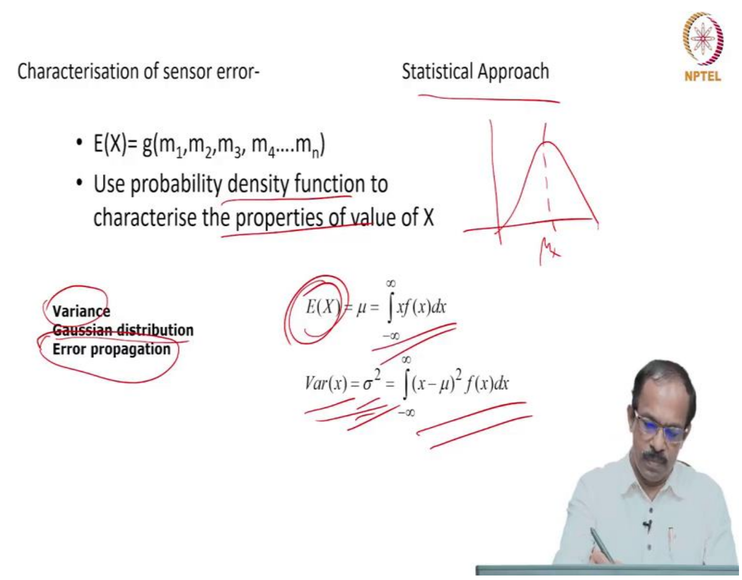

So, normally as I mentioned the statistical approach is basically you get this the μ as a function like this and we will get the variance or the σ^2. For that function can be provided, when you have a probability density function ok. So, we can actually predict this as I mean you can actually show this as a distribution function, the random errors and then, say that the μ of this is like this and then, σ is σ^2 is given by this. And therefore, the E(X) can be or the density function sorry the mean value can be obtained and similar. $E(X)= g(m_1,m_2,m_3, m_4....m_n)$ Therefore, we will have a good probability distribution for the sensor.

So, every robot, every sensor will assume a variance and we assume that it is a Gaussian distribution and once we have that one, we can use something called an error propagation model to identify the extent of error in an estimated value also. So, what does it mean is suppose, I use let me see whether it is there ok. Anyway, I talk about this error propagation slightly later also.

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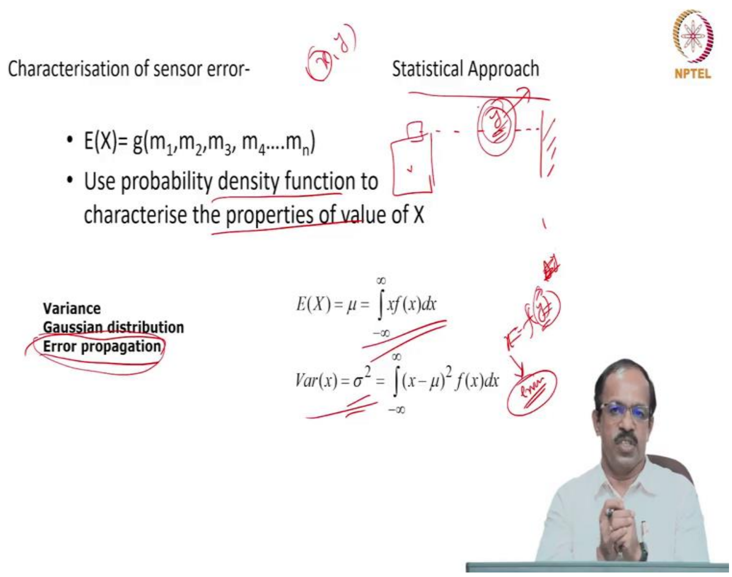

But what we do in the error propagation is that suppose, I use a sensor to measure the distance the robot is here and I use a sensor to find out its distance y from here ok. What is the distance from to this? And then based on this distance measured, I tried to find out what is the x y position of the robots. So, now I know if I know y, I will be able to get x = f(y). So, some relationship is there. I can find out the position x, if I know y. So, that I put this x is a function of y.

So, if I know y, I can actually get the x. Now, the problem is that I am using this measurement and then getting the y. So, y itself has got an error. So, when y has got an error. There is an error δ_y in y ok. I cannot say δ_y. It is a random error; it is a distribution. This random error is there in y, when I estimate x, x also will be having an error in x also. So, what will be the error in x, if there is an error in y? So, I need to find out what will be the error in x, if I know the error in y and that is known as the error propagation model.

So, we will be able to predict the error in the estimated position of the robot, if there is an error in the measure measured value using the sensor. So, that is basically the error propagation. So, we need to know the error in the sensor and then, what is that error doing or what kind of effect that error has got in estimating the position of the robot. So, we will have an additional error coming into the positioning of the robot because of the error in the sense.

So, first thing is the error how do we actually model the error itself and then, the effect of that error in the estimated position of the robot or estimated parameter, any parameter that the position or some other parameter you are trying to estimate. So, what is the effect of this error on that one also need to be understood. So, this is the way, I mean this is these are the difficulties or the challenges in using sensors for estimating the position of the robots or estimating the environmental parameters or getting the perception of the environment and giving that information to the robots.

So, with this background, let us look at some of those sensors which are used and what are the basic operating principle of those sensors. And then, see how each sensor is leading to errors and how these errors can actually be compensated by either by probabilistic approach or by using some kind of sensor fusion, where we can use multiple sensor data and then, use that information to reduce the estimated error in the robot parameters.

So, we will see that in the next class. So, tomorrow, we will look at the various sensors and then, try to identify the their performance parameters and the principles of operation ok. So, thank you very much, we will meet in the next class.

Thank you.