Foundations of Cyber Physical System
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Lecture No # 06
Module No # 02
Real Time sensing and Communication for CPS

Hi everybody. Welcome back to this lecture series on Cyber Physical Systems. So, we will be just starting over with the week 2 lectures here. So, what we will be talking about here is how real time sensing and communication happens in Cyber Physical Systems?

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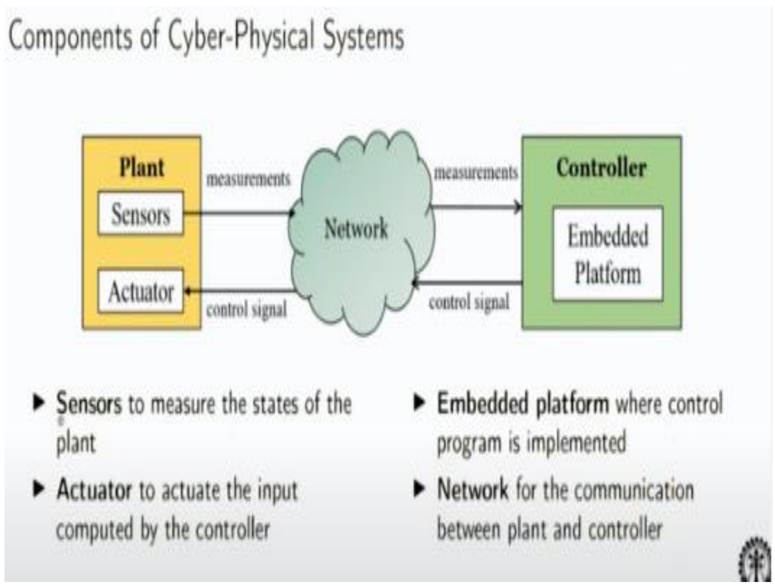

So here we have a simple high-level model of a CPS and which is trying to tell you that what are, the rules that sensors and actuators play. So as you can see that there are sensors which are gathering measurements and they are sending those measurements over the network. There is a control software which is running on an embedded platform and that is using these sensed values to create a control action.

And that control action may be transmitted back through this channel to the actuator which will actually implement this action in the plant. So, like we said that this channel can be a wired bus it can be even the internet it can also be wireless real time network. So, what we will do is we will today first talk about I mean these sensors because sensors form real part of a CPS, right. I mean sensor I mean what sensors do and how do they work.

A bit of knowledge on that will actually help you to understand that how CPS systems work and what is the impact they have and what can happen if measurements go wrong and or more, so that I mean why do measurements go wrong? So, this these ideas can always help in creating a robust Cyber Physical System.

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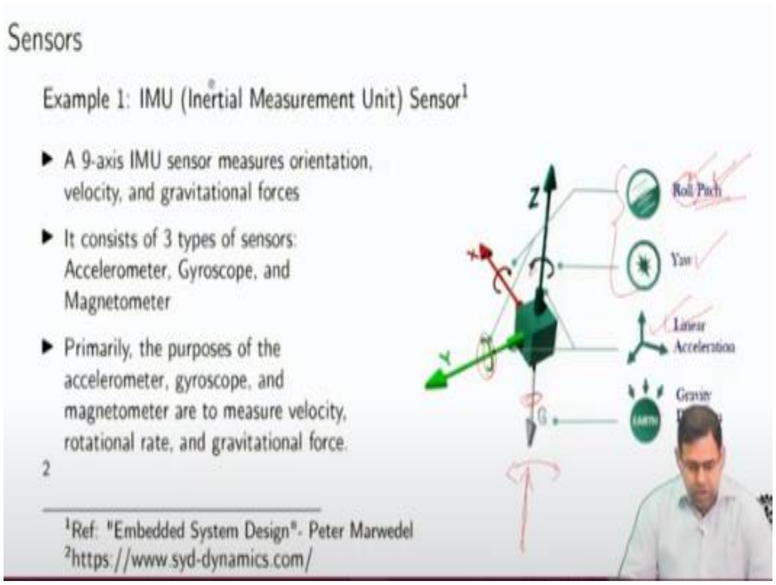

So, we will just have some introduction on different sensors. So, we will just list a set of popular sensors that are typically used. For example, we will talk about IMU sensors Inertial Measurement Unit full form. That is the Inertial Measurement Unit the acronym is IMU. You must have heard of this. This IMU sensors because they are nowadays kind of ubiquitous around us right. They are part of so many different kinds of devices around us.

So, what does this really do I mean? It is basically a collection of multiple sensing suits. So it the multiple this, these different sensors overall they provide you with sensed values of many variables which together give you the orientation of a system. Let us understand what we mean by orientation of a system? So let us say we are in 3D space and we want to understand that if the vehicle has got linear acceleration in the x axis, y axis or z axis.

So that is a measurement which may be required by many different applications right. Now think of what are the other possible measurements that may be required. Now an example of that I mean let us understand. Well, this is pretty standard. I want to know that something has a movement in

X, Y and Z direction which is fine. But what are the other things we may be interested in or is this all apparently what happens that this acceleration values in these different directions may not be all that define the orientation of a system.

Because they just tell you, well, from this acceleration value if I sample them enough over a time period, I can know what is the speed, what is the distance covered which is fine. But I also do not know many other things which may be useful in several applications. One is what we call as yaw. So, what is yaw? So suppose you have something moving forward in a specific direction and you are interested to know if I mean you are not only interested in this linear acceleration you also want to move sideways, this way or this way. So, this is what we call as a yaw movement.

If this is your X direction then I mean around the Z axis you see the system is rotating, like you see, the system is kind of rotating here around this Z axis. If I do that then my system along the X axis is moving to the left or the right. So as an analogy think of an aircraft moving. So, for an aircraft, the pilot typically controls its orientation in terms of yaw, roll and pitch. So, the linear acceleration is fine, right. It just talks about the rate of change of the its position and speed in the X direction, Y direction and the Z direction, but that does not really define the complete orientation of the system.

So, to change its positions the aircraft would also need to rotate around its Z axis to go left hand side, left and right with respect to the X axis. So that is yaw. And similarly, it can also rotate around the X axis, right. You must have seen fighter aircrafts rotating around pitch X axis. So that is what we call as roll, right. And similarly, if it is rotating around its Y axis that is the movement that aircraft will do to go up or down, right. So that means it is changing its pitch angle, right. So, the pilot using his joystick can control the aircraft's roll, pitch and yaw, right.

So, these 3 things tell you what is the orientation of the aircraft and other are the usual things the linear acceleration and the three axis, right. Apart from that you see, based on the vehicle’s movements and speeds etc., we can measure that what is the G force that is acting on the vehicle, right. So, that is another force I want to know about, right. So, all these things together tell me what is the orientation of the system, what is the velocity and what is the what are the gravitational forces?

So, to sum up, the orientation is given by this yaw, roll and pitch. And I have the movement being described by this linear acceleration and corresponding velocity and position in across the 3 axis and the gravitational field value. So, the thing is, when you have a moving body which is subject to different forces and that moving body can generate motion, it is possible for it to do generate the motion based on its own internal systems and taking into account the effect of the environment. It can do all these things.

It can it can change its roll, pitch and yaw angle and it can change its linear acceleration values, right. And depending on its movements it we can also see that, what is the effect of gravity that is happening on that. Let us say it is falling down too fast, right. That will have a different value of then it is experiencing a different value of gravity just as an example.

So, to measure all these things its complete orientation and velocity and gravitational forces the IMU sensor actually uses 3 individual sensors together. These are the magnetometer, the gyroscope and the accelerometer. So, the accelerometer will give it all the linear acceleration values in the 3 directions. The gyroscope will tell it what is its orientation with respect to roll angle, yaw angle and pitch angle, and the magnetometer will measure the gravitational force, the g value which is acting on it.

So, we can we can use all these individual sensors which together is the IMU to give some information about a physical system, motion, orientation and I mean and that is kind of going to help you to design a suitable control law which is going to manipulate its motion. So that is we are not going into the details of how this thing works here. We will go into the details of some sensors maybe not order of them but that details will be kind of more like an overview here.

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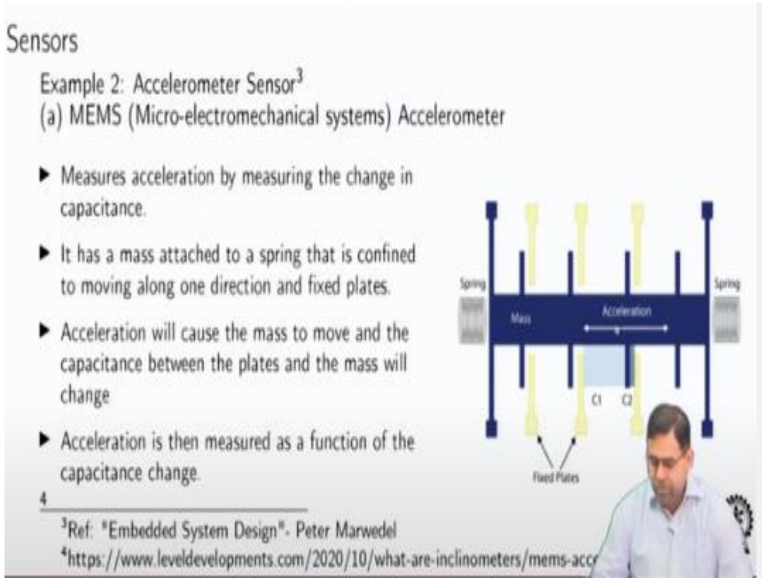

So, we will start with the accelerometer sensor. We are taking an example of a MEMS accelerometer here. MEMS full form is Micro-electromechanical system accelerometer. So, let us see. So, like we said that the accelerometer, what it does is? It measures the velocity or in other way the linear acceleration in the different directions, right. So, this kind of Micro-electromechanical accelerator, what it does is? It will be measuring the acceleration using change in capacitance.

So, let us understand. Suppose you have a spring mass system like this, so, what is going to happen is? When your overall bigger system is going to accelerate, here inside it there is a spring mass system. So, since it is accelerating you see, this mass, these are small object of this particular shape which is being kept suspended between the springs. And there are some fixed plates here. The fixed plates means they do not move with respect to the bigger system. If the bigger system moves along with them the fixed plates also move with the exact similar velocity.

But this mass is kind of suspended. So, the mass will have an acceleration it will compress and enhance the spring based on the acceleration. And what will happen is, it will have a movement right and that will change the distance between these plates, right. So, this let us say this plate is here and these fixed plates are here. When this is accelerating forward, the distance here between this plate and these 2 fixed plates is going to change. And that will lead to change in the value of the capacitances C1 and C2, right.

So based on that change I can measure acceleration as a function of this capacitance change, right. So, this principle is more based on a spring mass system and based on the spring mass system, how the capacitance changed, right.

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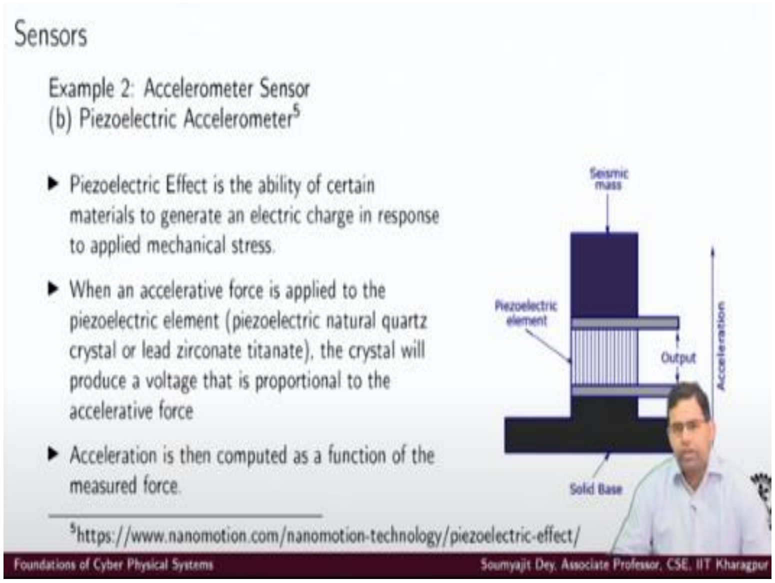

Similarly, we can have accelerometers based on piezoelectric. So, piezoelectric as we know they have the ability to generate an electric charge in response to some mechanical stress that is applied, right. So, if you put pressure on a piezoelectric crystal, it will generate an electric charge, right. So, let us say you have a seismic mass here, right and you have this piezoelectric element. Now you give some acceleration here if and this is a solid base.

So, if you give some acceleration here what will happen is? It will generate the seismic mass that is here. It will generate a proportionate force on this piezoelectric body and accordingly it will give an output voltage, which is proportional. So, essentially what is happening, we are generating in all these sensors, my basic principle is, I am generating a proportional change in some electrical quantity voltage-current based on change on capacitance here, based on change on this output voltage here and that is being used to measure the physical quantity. So that is the kind of principle on which this sensor should be working.

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Now similarly I can also have a gyroscope sensor. I mean MEMS gyroscope sensor, which can be used for measuring those an orientation related elements like roll, pitch, and yaw. And their primary principle is to use the Coriolis force, right. So this Coriolis force is a fictitious force that acts on a moving body when it is rotating with respect to some central point, right. It is going to act orthogonal to the angular velocity, right, and the linear velocity under consideration, and the effect of that Coriolis force can be felt and accordingly these values of orientation variables can be measured. We are not going into the details of this. You can look into these different sources that were citing from which we have taken all these examples.

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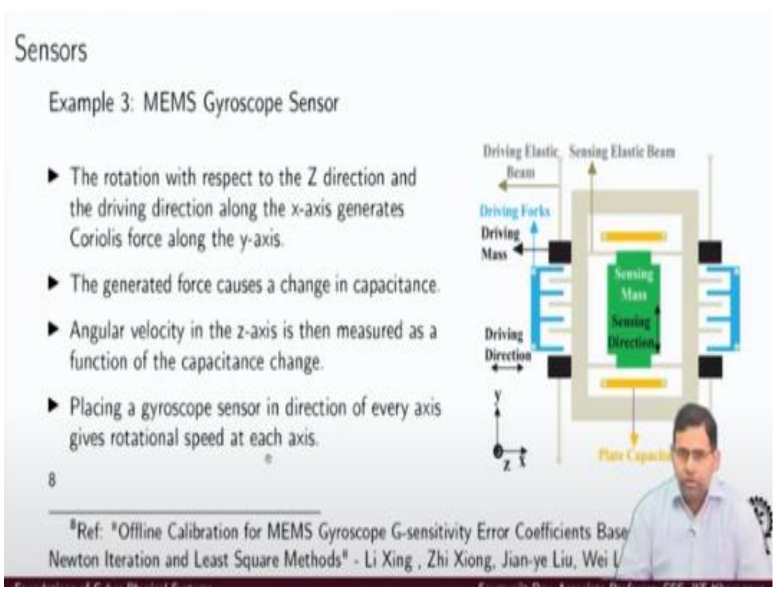

You can also have MEMS gyroscope sensors right. So, what they do is again, they have a principle of changing capacitance. With respect to this change in capacitance you can actually measure this velocity in the in the different directions. So, when this gyroscope is rotating with respect to the Z direction and there is a, and the driving direction along the X axis it will generate a Coriolis force along the Y axis.

So, if you remember the principle that we talked about that when you have Coriolis force it is going to act orthogonal to the linear as well as the angular velocity, right. So, when your vehicle is having a linear motion along the X axis and there is a rotation along the Z axis, the Coriolis force will act along the Y axis, right. Now again this force can be used to generate something like a change in capacitance, and similarly as a function of that I can also measure based on this where the system is being configured here I can also measure the, what is the angular velocity in the Z axis. So, what I can do is, see in this kind of a setup, like we said that with one such gyroscope I can measure the generated force along some axis right. So, let us say here you have this Coriolis force acting in the Y axis and there that will be inducing the capacitance and based on that capacitance proportionally what I get will be volt a voltage change, right.

So, that essentially is acting as an estimate of what is the angular velocity in the Z direction, right. So, lets again repeat this. We are considering a vehicle which is driving along X axis and along with that it is also rotating around the Z axis. So basically, you are negotiating a turn and I want to understand the amount of angular velocity, because that is something that will be used by several controllers to do some control action on the vehicle.

So, if I want to do I that I can always use this principle. I will use this gyroscope sensor, it will generate the force along the Y axis, it will create a change in capacitance and that will have a corresponding change in voltage or current, and that will give me an estimate of the angular velocity in the Z axis. Now for each such possible axis of motion, I will have a suitable gyroscope configured along the other axis.

So just like I can use one gyroscope for Z axis I can use two more gyroscopes for considering the rotation around the X axis and Y axis right I mean if they are necessary. So, I can have a gyroscope in directions of every axis and that will give me the rotational speed across each axis. So, this will give me the orientation information in full that is the roll, pitch and yaw.

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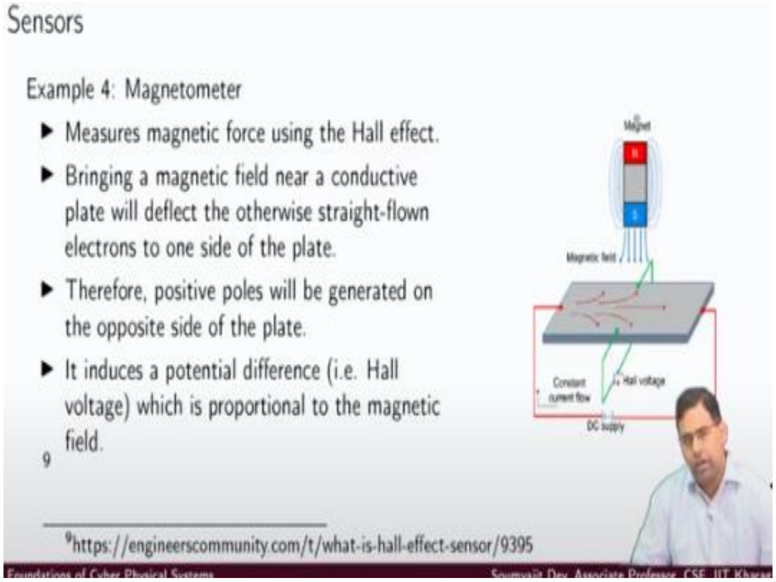

Now, the other thing we will talk about another very important sensor that is the magnetometer. So, what the magnetometer does is it uses Hall effect. So, Hall effect is basically an electromagnetic phenomenon which says that if you bring a magnetic field near a conductive plate, it will deflect the straight flow of electrons from its standard flow. So, let us say you have an electric field here, right. So, if electrons flowing like this. Now if you are bringing a permanent magnet here. What will be happening is this flow will be disturbed right.

So, the other way state flow on one side that will be disturbed and this will do something like, it will create a potential difference across the plate. So let us understand, there is no straight flow, there is a deflection happening and that is going to create this Hall voltage which is appearing across the plate right, and this is the constant current flow. Now suppose I bring this magnet, I get that magnet back, again I bring this magnet I get that magnet back. If this kind of a constant motion is happening, what will happen?

This Hall voltage will appear and disappear appear and disappear right. If I add a suitable resistance and measure the current across it, I will see a current pulse appear and disappear, and that would be happening proportional to the speed with which I bring this magnet near and take it far, right.

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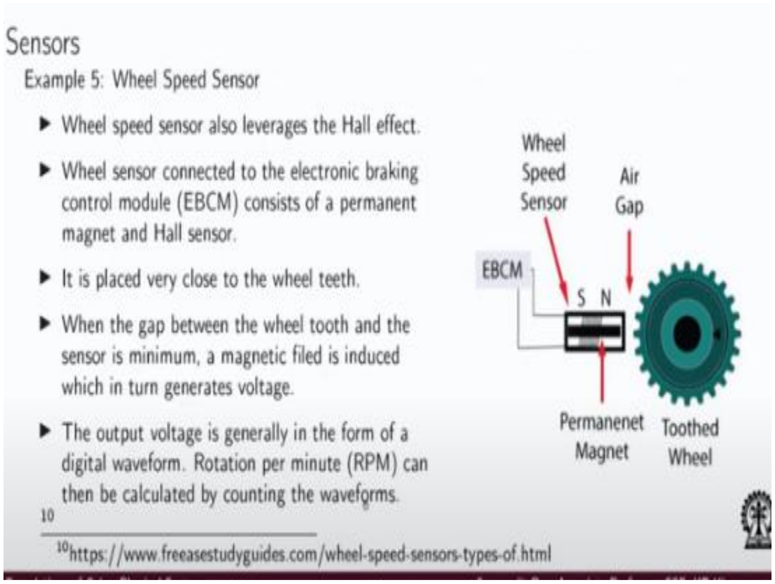

So, this principle is very commonly used in the wheel speed sensor of vehicles. So, what they do is, they will attach a wheel like this. So, they will attach a wheel like this in the wheel well and then they will have this kind of permanent magnet. And there will be air gap and this is the wheel that is there with teeth, right. So, when this wheel is rotating at some speed, in a proportionally a number of teeth crossing this magnet will keep on changing, right.

So, what happens, this wheel sensor is connected to the electronic braking control module which consists of a permanent magnet and you have placed a Hall sensor across it. Now when the gap between the wheel tooth and sensor is minimum what will happen is, a magnetic field is induced which will in turn will generate a voltage, right. Because it is going to come near to the magnet and go far, it is going to come again near to the magnet and go far. Whenever the teeth is facing this magnet, that means this plate is near to the magnets, right.

So, there will be a Hall effect voltage that will be created and then if then again it will disappear when this truth goes far away. Another tooth will come and again the voltage will appear, right. So, this output voltage will basically be having a digital waveform and the Rotations Per Minute can be actually calculated by calculating, by counting the number of peaks in the waveform right, so it is as simple as that.

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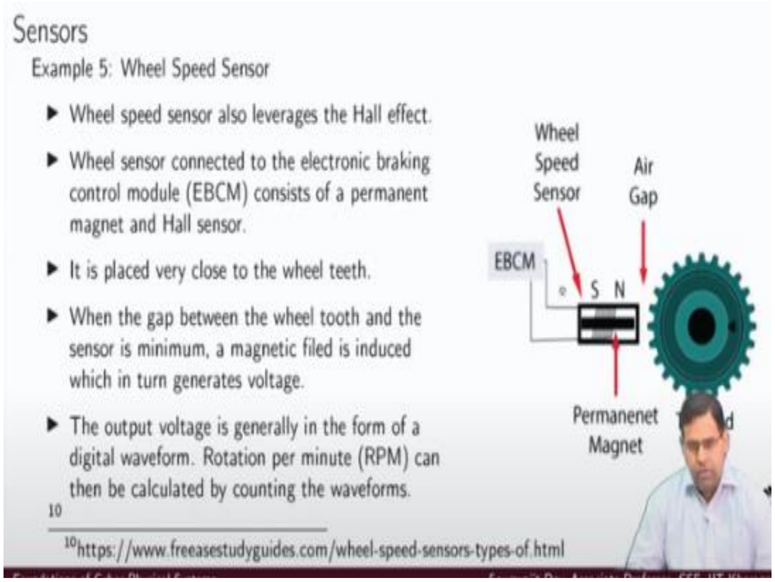

Now something about sensors, so we spoke about several different kinds of sensors that are used we talked about IMU sensor in general, which actually contains the linear acceleration sensors, the orientation sensors, the gravity sensor. And then we talked about some accelerometer system using capacitances which can be used for sensing the acceleration. Then we also talked about accelerometers which can be built using piezoelectric crystals.

So, these are the earlier one is being using microelectronic spring mass damper system, right. And then we talked about these gyroscopes and how what is the principle on which the gyroscope is going to act and how gyroscopes can be used to measure the rotation around some specific axis. And having multiple gyroscopes can give you values of rotation across multiple such axis, right. And then we also talked about magnetometer using which you can actually measure the Hall voltage value.

And we talked about how this principle is very useful in a very important application which is like when your vehicle is being driven, how to get the estimate of the actual speed, right? So that is kind of measured using this kind of wheel speed sensors. So nice. With this we will be ending this lecture. Thanks for your attention.