Foundations of Cyber Physical Systems
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Lecture – 04
CPS : Motivational Examples and Compute Platforms (Continued)

Hello, we will come back to this course on foundations of cyber physical systems. So, let us get on with the ah get on from the point where we left.

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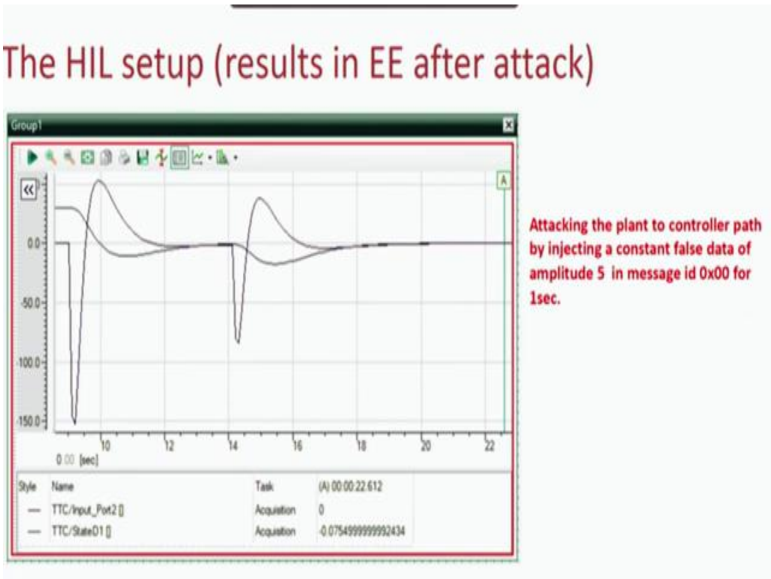

So, I believe we have been discussing about HIL setups and how they can be used for analyzing. Cyber cyber physical security applications. Ah So, these are the different things we just want to introduce to you as concepts in this week and we will also like to introduce some other fun to use softwares which are very much prevalent in this domain.

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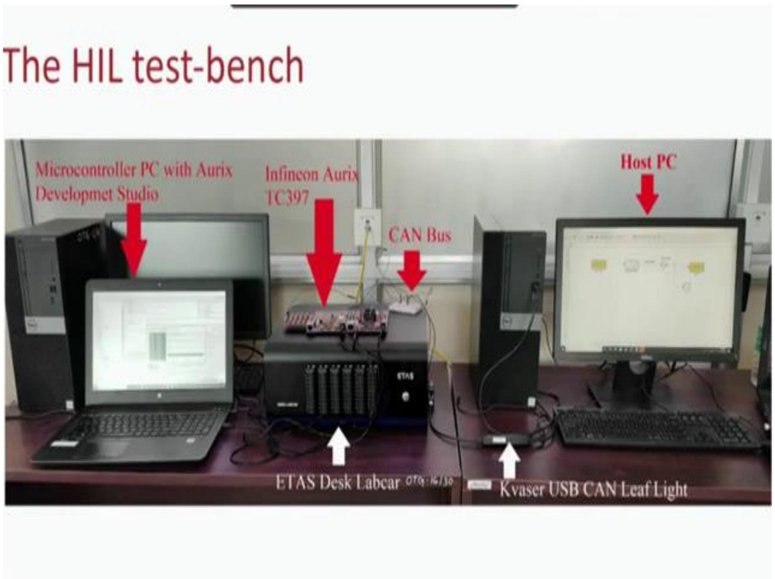

And before going to that let us just look at this testbed picture. So, you can see that ah this is an example HIL and this is simulating the plant model that we talked about. The plant model can be coded using ah Matlab simulink toolbox, one of the popular tool boxes which is very much used in cyber physical system design. And this would be controlled by some software and that software is going to run in this embedded processor board.

And this is being programmed from another laptop here where we are running that infineon IDE which we showed you in some previous screenshot. So, this is like a setup through which you can analyze this kind of systems but that is not the only way to talk about cyber physical systems. I must also put in some ah caution here in case you do not have a hardware in the loop simulator.

Does it mean that you cannot work with CPS or cannot learn CPS or cannot simulate CPS? Absolutely no. Like this is only going to give you the real-time guarantee. Right So that is very much required for real system implementation stuff like that. But if you want to learn the concepts there are pretty much well known simulators also available which you can download in your PC.

There are softwares like open modelica which you can just download in your PC. And you can actually simulate various kinds of lab scale ah or I mean cyber physical system examples for that matter. Nowadays, python provides you with lot of simple libraries ah using which are of course, free and free and open course. You can just download them as CPS examples and simulate analyse and and do your kind of basic design also.

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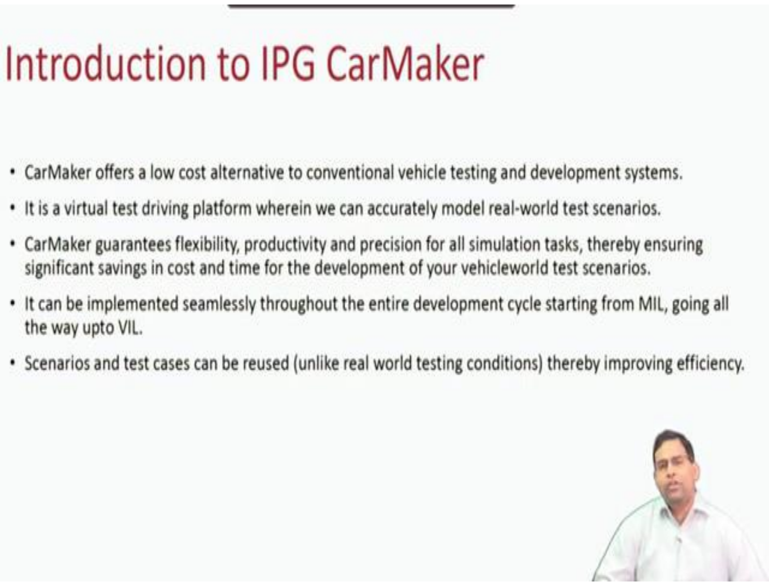

So, we will just ah take an example of another software ah called the carmaker. And of course, I must say that this is again an example software and there are very, very much other offerings in the same domain. So, suppose I want to simulate vehicle dynamics in ah in a lab scale setup. What can I do? I must say that this is the commercial software but there are lot of open source software also available.

We will list them out by the end of the course and we will also give you some demonstrations of that of such open source software offerings which which are in this domain. So, what this kind of softwares can do is, you can you can Sim simulate vehicles ah inside a traffic scenario, inside a road scenario, pedestrian scenario like that. And but how does it help? Is it I mean almost like playing ah need for speed kind of game? No, not really.

This is much more, I would say educational and academic also. In the sense that you can design your kind of control strategy for your vehicles. You can design your kind of ML based driving strategy for your vehicles and you can see that how they perform in a simulation world.

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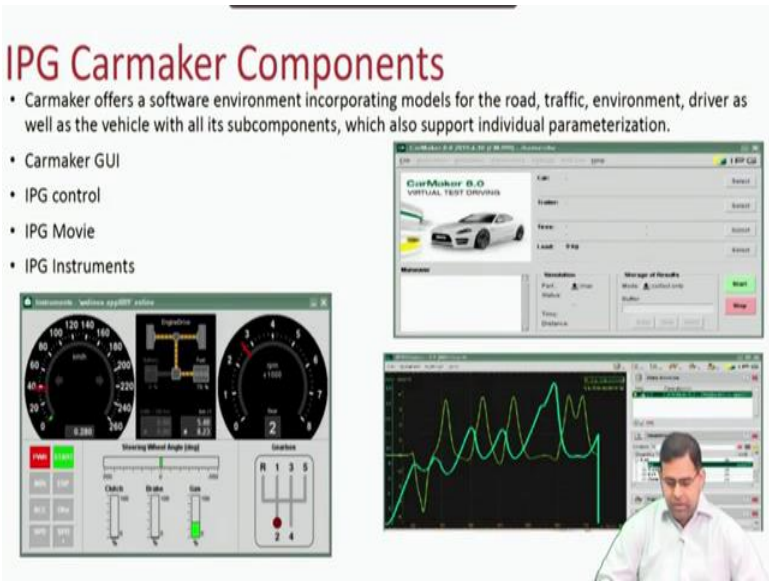

So, there are softwares in this domain for doing that and this is just one such example. So, this is just some example screenshots that you can. You can drive that vehicle in a virtual world using some softwares and you can. You can actually, see that what are the different vehicular parameters and how they are performing those things you can see. Right

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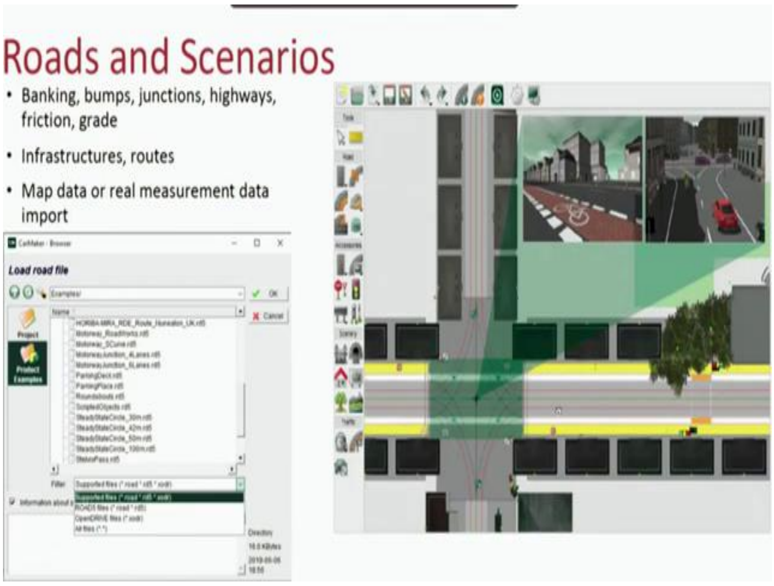

Now, this is an interesting ah GUI of that the that the software offers using which you can actually, import different scenes. ok Road scenarios of different kind of friction, different kind of climatic condition. And accordingly, you can create a road scenario and you can run your vehicle on such a specific cross road scenario.

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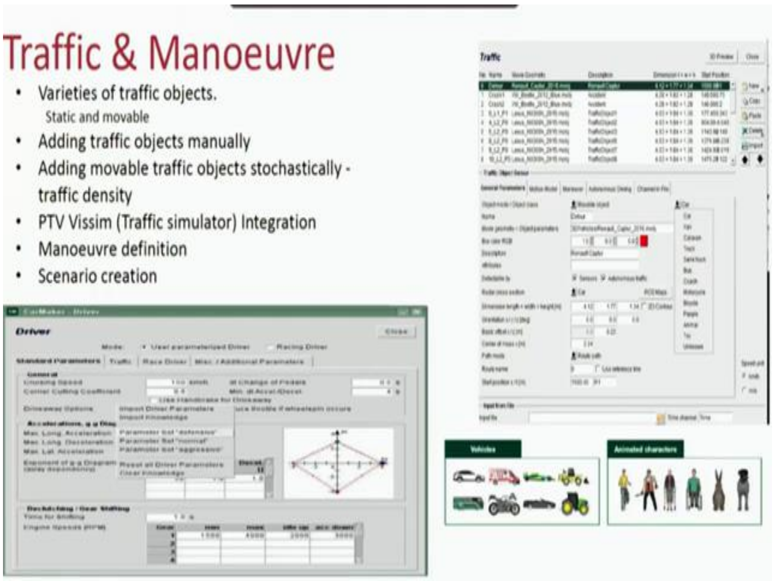

So, you can also include traffic, ah following some other simulator, you can integrate such other simulators also inside this but I must again repeat. This is just one example there are many such simulators and there are also many in the open source domain which we will talk about. For example, there is a Carla, Carla is an open source simulator which you can download and work with for vehicle driving strategy and those kind of analysis.

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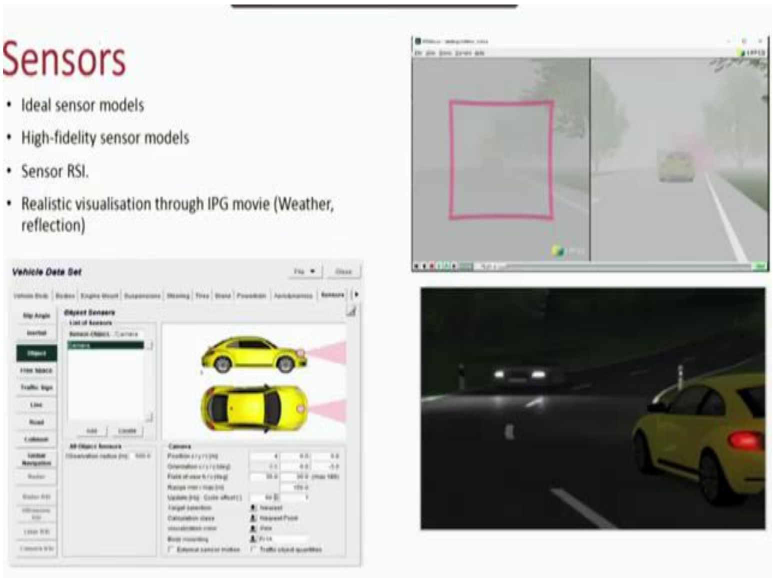

Now, the interesting thing that this offers is suppose you are trying to create and create some create some automotive software some software logic. Let us say you are going to and that software logic is going to use some sensors. So, what you can do is you can have some software sensors inside this software. So, whenever you can select a vehicle of your choice with this vehicle, it is ah parameter should also get loaded like size, weight, etcetera, etcetera.

As you can understand, the vehicle's movement will be a function of all those vehicle parameters by basic laws of physics. Right Now, you can add sensors, you can add radar sensors, you can add camera sensors, not the physical sensor but a software model of the sensor here. And then you can actually, see the software feel that the sensor is generating. So, let us say I import a car in this scene and now, when the car is running, I have configured this car with a camera sensor. Ok

Now, I can also see using another scope that this software provides that what can the what the camera is actually able to view? So, I can see this kind of scenarios. So, let us say this is a foggy scenario. So, I can really see that. Now what is the advantage? I can use this to build complex software Ah for controlling a car. I can really do that ah by using this kind of ah software frameworks. So that is the point that you can. You can actually program vehicle dynamics.

Just like you are writing C programs. These are kind of different kind of program right because you are now going to control the vehicles dynamics based on sensory inputs that the vehicle is getting. right So, ah that is what we will really call that I mean ah with this advent of autonomous driving and other craze recent crazes, what is happening is ah you have lot of scope to enhance your vision of programming.

You can you can not only program in a desktop software, you can program a real-time system. A real-time system which has got lot of sensing sensing happening in real-time and it is going to do some computers on the sensing and there will be feedback also. right For example, I can. I can write a program which will control the vehicle's movements and that program will work based on whatever sensory inputs.

For, for example, I can add a radar, I can add a lidar. A lidar can give me obstacle distances and I can write a program to control its brakes, steering accelerator based on those inputs that I am getting from the sensors. And the magic that will happen is I can put my vehicle in a in a self-designed road scenario and the vehicle will move according to my program and I can see that how my control strategy of the vehicle is performing.

So, all these things are possible with this kind of simulation platforms that are quite well known nowadays. But ah of course, you have to be aware of how to do such programming which are kind of reactive and real-time programs. And how so, just like our normal C program will be taking input, let us say from the console or from some other way from the user. Here it is taking inputs from sensors.

Of course, the sensors are also simulated here but your program here is taking input from the sensors. It is doing something what it is doing is it is controlling the motion of a physical body and that the story does not end here. What the program does now will affect what the program will do again in the next round. So, based on all these things, your program has to be written.

So, essentially, you are writing a control software logic which is going to control the movement of this vehicle. And so that is really fun because you can, you can actually, apply such concepts in lot of domains. So, there are other simulators in this domain using which you can do such control over of some other physical systems. So, as you can see that you can take up any other physical system, let us say a drone. Right

In Matlab you will find tool boxes using which you can have drone models and you can control their movement inside such predefined graphical scenarios. So, this brings us to this idea of programming of intelligent systems and we will do quite a bit of it. Why, as we proceed in this course.

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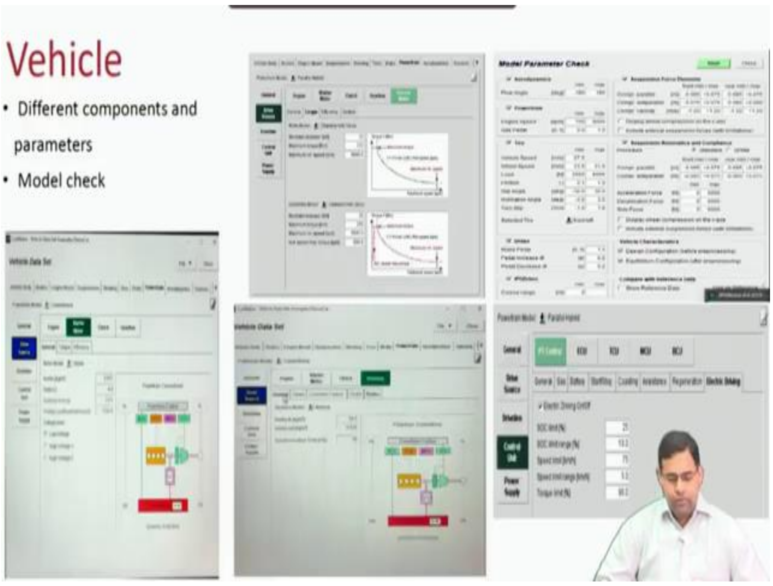

So, some more screenshots on different vehicular parameters, so, you can actually, control quite a lot of things in this specific software, like you can actually, select control logics. You can write your own custom control logic. You can

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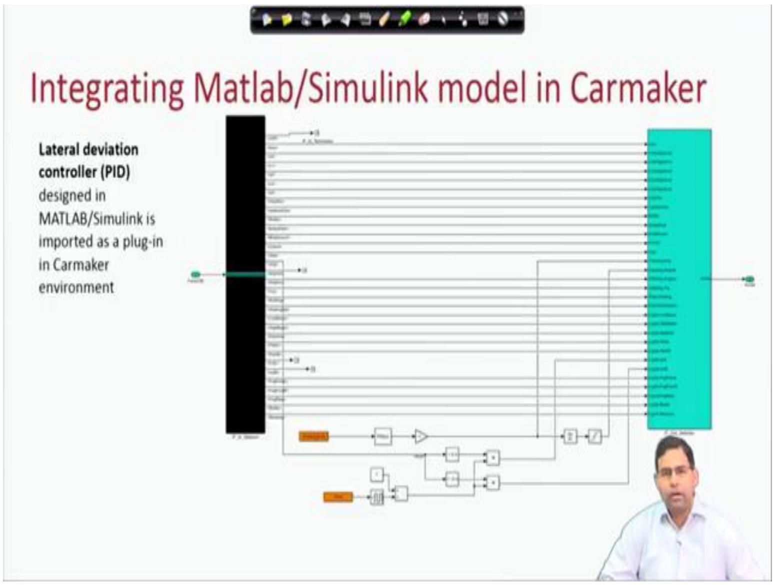

So, all these things are possible in these and many other simulators that are available in the market. Now, not only that I can write a sim control logic in Matlab and I can interface that control logic with this software. So that now, what will happen is my control logic of some vehicle is in Matlab it is running like I said, the CPS simulation is all about core simulation among many many softwares. Right

So, in Matlab you are running the control logic and it is passing the control commands computed to carmaker and you get a feedback to Matlab that well, the carmaker sensors will tell you that I can, due to the break, you pressed the distance with the previous curve became this so that information will be updated back from carmaker to Matlab. Again, the control logic will fire in Matlab.

And again that a break command or accelerator command will be transmitted to carmaker and this loop will continue. So, this thing is also possible to be done.

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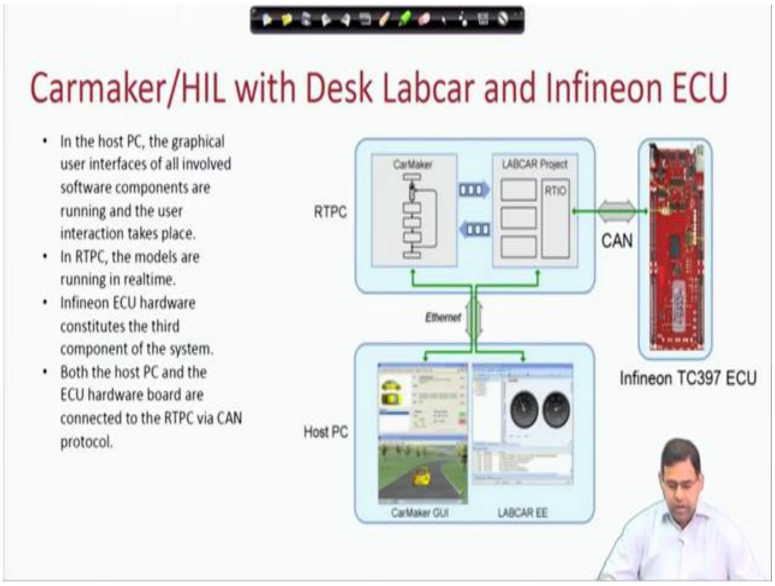

And there is another thing possible like we introduced that hardware in the loop simulator. So, I can run this carmaker kind of software in this kind of ah labcar or some other hardware in the loop simulator. So, any hardware in the loop simulator and I can have my control logic written as software program or maybe I wrote the Matlab program and I generated the code. And I compiled it ah compiled that software that code for some target board and then I can interface this board with the ah hardware in the loop simulator and the carmaker software is running on hardware in the loop and it is controlled by an actual C program which is running in this board. So, this really becomes very much nearby to programming of vehicles and running and your weight your C program controlling the movement of the vehicle. The only thing is, you are not using the real vehicle but you are using a dynamical model of the vehicle which is quite detailed in case, it is a commercial software or and you are, you are controlling that vehicle and the vehicle is moving around inside a road scenario that you have created inside this software. So that is quite, I think, fun to do that. You just do not write normal programs for desktop systems but you write programs for embedded processors and your program does quite a lot. It controls a real physical systems dynamics through this kind of a software software and hardware interface.

So that is something which you can really do here. Now, in case you, the question may come suppose I do not have this costly things. I do not have an HIL system, I do not have a commercial version of carmaker does not matter. You can You can get a very small let us say 200, 300 rupees cost ah embedded processor, on which you can download your Matlab code through an embedded coder kind of code generator from Matlab you can write your controller.

You can generate the C code from Matlab. You can compile that code to some to your very low cost, embedded processors. You can use an open source vehicle and road scenario simulator in your PC then all that happens is your PC based simulation has to be interfaced through USB or serial port or something with your embedded processor where the C code is running. So, there you have again an example of a physical body simulation being controlled by a program running on an embedded processor.

So, typically that is what CPS will be about more or less. Ok That you have ah real physical system. You do not have it right now. You have, it is model, it is running on your PC. If you have a costly setup, you can run it on an HIL. If you have, if you have more budget you can purchase that real software or if you are doing it as a student in a lab scale. You can just use the open source software.

Let us say Carla or something else and you can interface with that embedded processor board which is running your C program, so, all these things are possible and as you can see that it opens up lot of opportunities to learn about these concepts of programming, real-time system.

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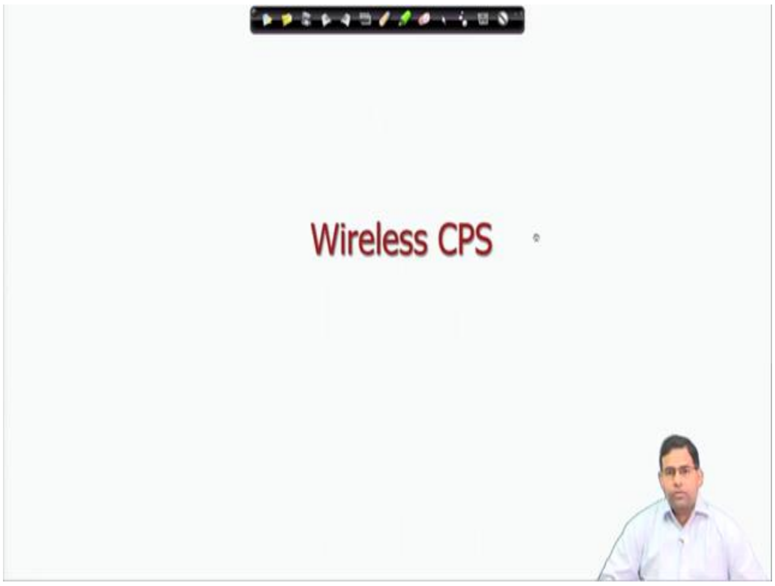

So, with this we will move on to another very interesting concept. That is wireless cyber physical system, so, what is all that?

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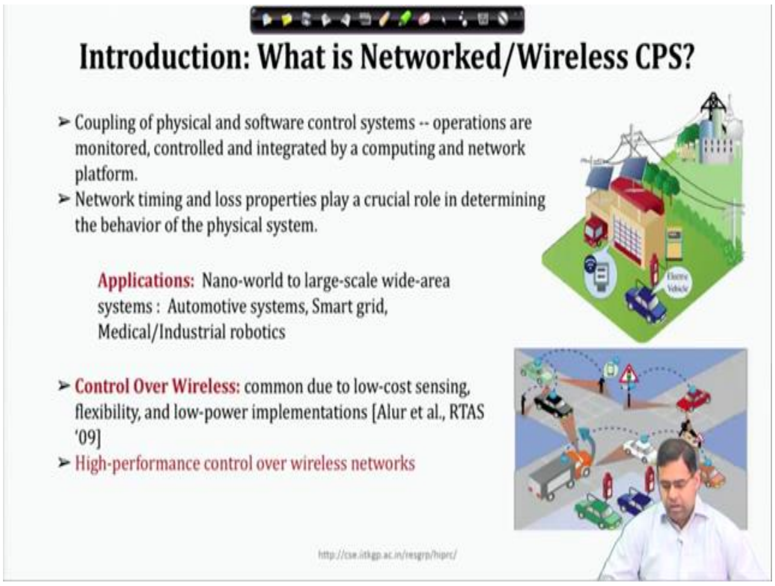

So, well, the basic idea remains fine ah that I am going to control Ah using some software logic, I am going to control or manipulate the trajectory of some physical system. right ah But the only difference is that now the communication that is going to happen between this physical system and this controller, it may be over a network and that too it may be a wireless network. ok So, the question is well, if it is a wireless network.

Then, ah you, you may have lesser bandwidth and you may have more number of packet losses happening. Ah So that is going to harm the performance that you may get in using your CPS implementation. So, the question is that how how how really we can address all those things like, of course, if we understand that the cyber physical system needs to be stable. Otherwise, because in because in most cases it will be a safety critical system. ah

But ah if the network issues like the network, uncertainties, the drops and packet delays start affecting my operations. it is It is a problem right which also means that well I will be using a wireless CPS ah but because because it is very much beneficial. right Because if I implement any cyber physical system without any wire ah it is. Ah it is like much much simpler and infrastructure to manage. So, given a choice one would always like to do that.

But, like I said, one needs to keep in mind the requirements that the the communication between the controller and the plant or the or the or (15:40) with the from the plant to the controller. They need to be real-time. ah The closed loop must work inside the sampling period that is real-time. And of course, being a wireless network there would be practice the I mean deadlines and packet losses. We have to. We have to be sure that those things do not do not lead to any kind of safety violation of the CPS.

So that is an important criteria which needs to be satisfied. Now, there are, there are lots of applications of having such wireless CPS. For example ah automotive systems. I mean automotive, most automotive, modern automobiles would have a would have a telemetry system through which it would be ah connecting to internet ah through using some ah some eSim that is already in place inside the vehicle. So, if there will be a network interface in most mode or modern automobiles and they would be used for a whole lot of activities.

So, for example, they can be used for diagnostics, they can be used for ah over the air updates. They can also be used for things like I mean gathering vehicle data and implementing geofencing. That means the user must ensure that the vehicle never crosses some some predefined boundaries inside Google map. Let us play so, such things ah not only that there can also be some serious, real-time applications.

For example, platooning. So, vehicles may be exchanging control commands using a wireless infrastructure. And accordingly, a vehicle may be following a previous lead vehicle and there and this thing may be occurring in a platoon. That means there are more than two. There are many vehicles in the platoon. So, wireless also has applications in smart grid, so, smart meters installed in modern homes.

They may have wireless interfaces to the home area network through which it connects to the ah it is going to send information about power consumption to the ah to the operator to the to the operator of the grid, who will be accordingly building the consumer. And there can be such a for example anywhere, where we will like to have Ah I mean a cleaner implementation, a less evasive implementation.

We will like to have the network to be wireless like, for example, medical CPS. So, there are a host of whole lot of applications but, like I said that wireless also brings with it uncertainties and that need to be addressed.

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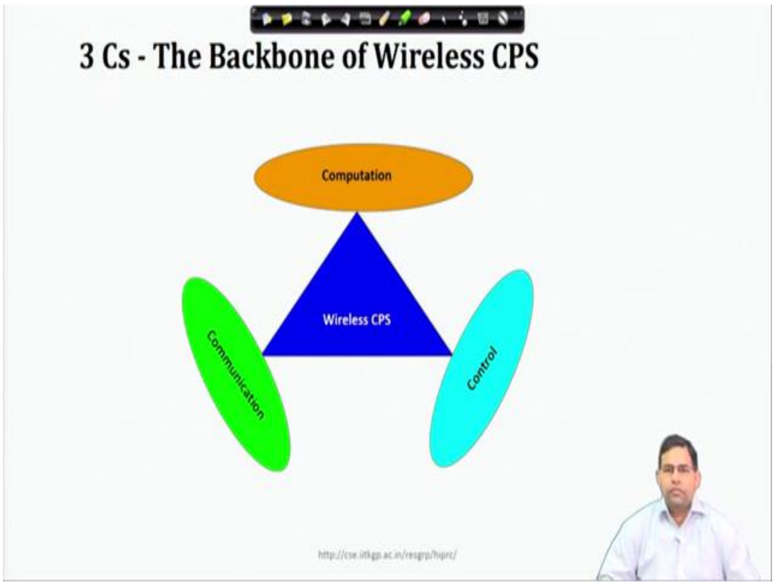

So, this is, as we say, are the backbones of wireless cyber physical systems. There would be control communication and computation and the communication is wireless in this case.

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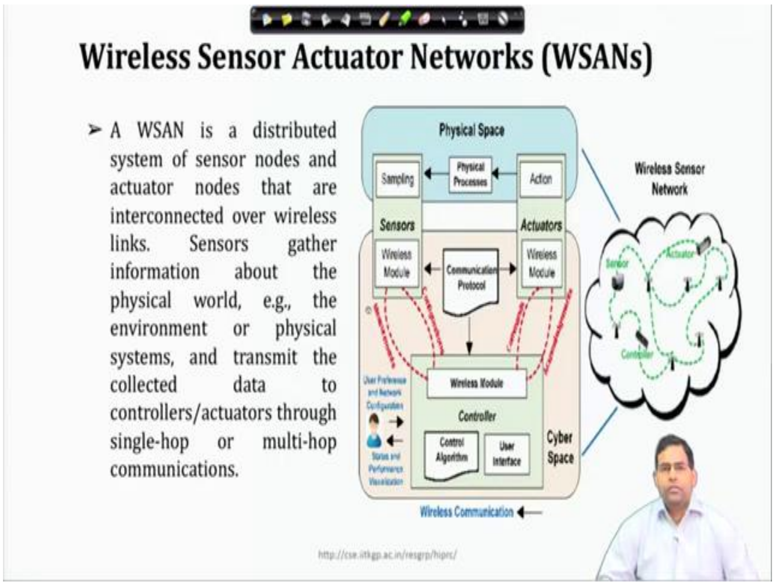

So, so, essentially, what are the communications that should happen using such a wireless mechanism? So, it is primarily the sensor right the sensors which are going to compute, I mean thus the physical process will be sampled and accordingly, the sensor will sense the physical parameters and it will have, have it is wireless module to communicate the measurements from the plant to the controller. and accord.

Similarly, the control logic would go back ah through a wireless interface to the physical actuator which may be attached to the physical process. Ok Now, ah this communication ah need not also be a one shot, one hop communication. It may happen that there are intermediate transmitters through which the message hops and is being forwarded to the final, finally to the controller.

So, it can also be a multi hop real-time network. ok It can be a single hop communication, it can be a multi hop communication.

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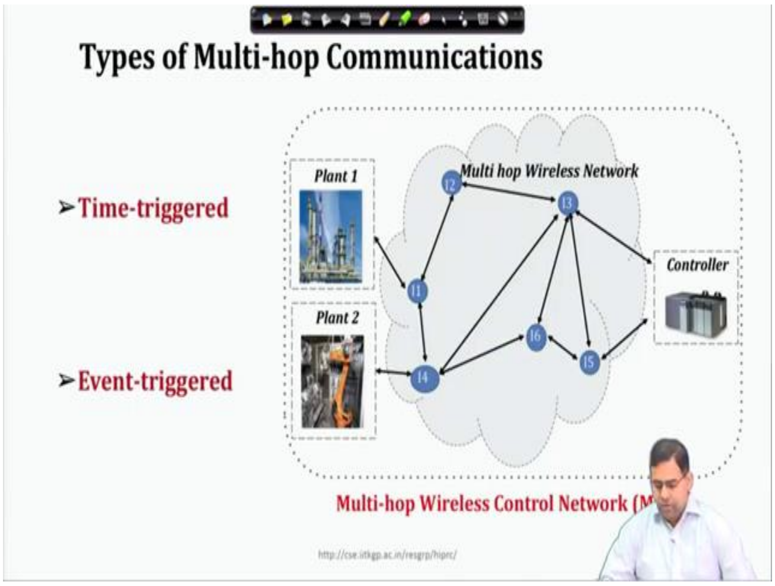

So, also ah I mean one very important application of such wireless CPS is would be in industry 4.0, where we are going to ah go for maximum automation of all factory works. right This will be reducing the number of physical workers who will be working with this physical systems, so, they will mostly be remotely operated through such networks. Now, in this kind of networks, the communication can be of two types.

It can be time triggered or it can be event triggered. Time triggered mean let us say the communication is always happening periodically. So, with clock ticks every clock tick in the system ah there would be a communication, the clock tick being defined as per the period ah the the period of messages, the periodicity of messages or it can be even triggered. That means in case some scenario happens.

Some property is satisfied so that event would fire a message and accordingly, the system wakes up and does something. So, both options exist.

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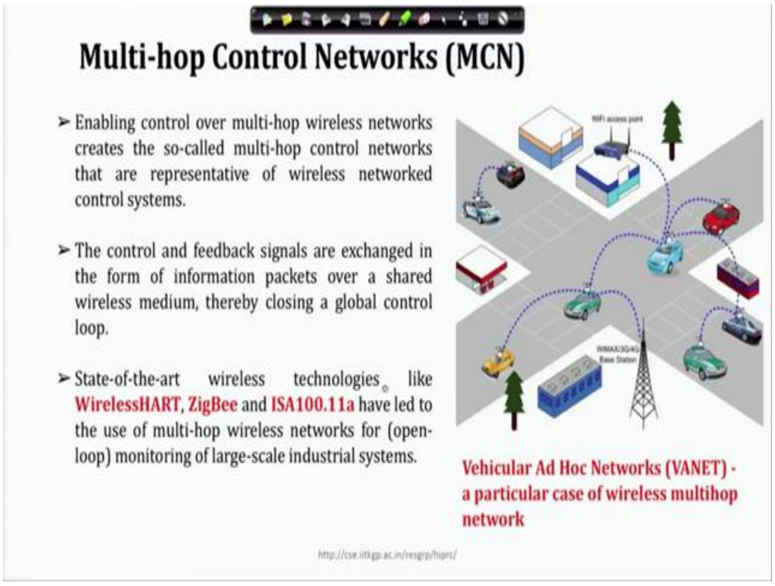

So, like we said that this kind of ah wireless CPS can also be multi hop and that has got its own application because Because of several issues this can happen. One can be a range issue between two bodies communicating among each other. The other can also be the amount of network data. The amount of network data which needs to be transmitted and received inside that real-time window may be so much that it does not satisfy the bandwidth constraint of the network.

So, in that case, you have to to have to add alternate nodes in the network and you have to root messages using alternate routes. And that may require multi-hop communication. So, all those all those requirements occur will be accordingly coming by and there are several such wireless technologies which are practically used. For example, WirelessHART, ZigBee and all these are standard technologies which are ah. So, basically what what are these?

These are wireless transmission protocols that are implemented in the at the physical level in suitable chips which are going to act as transceivers for the CPS nodes. And they see a lot of application in large scale industrial system.

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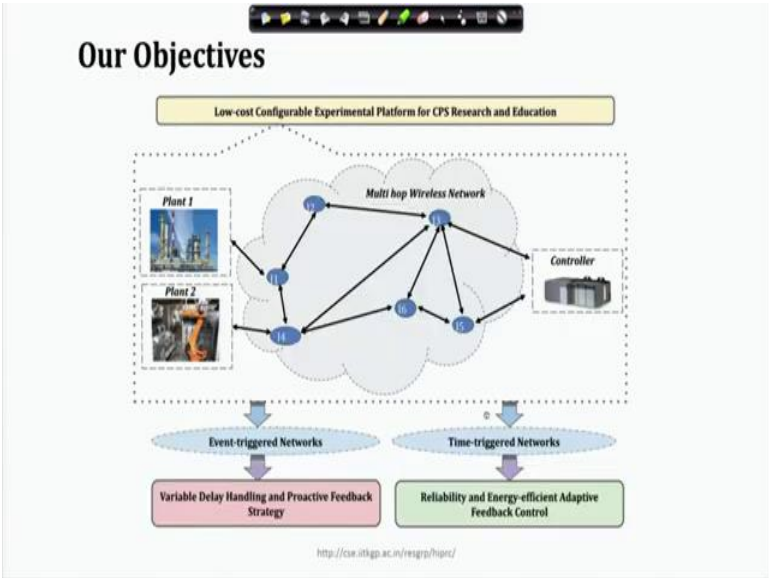

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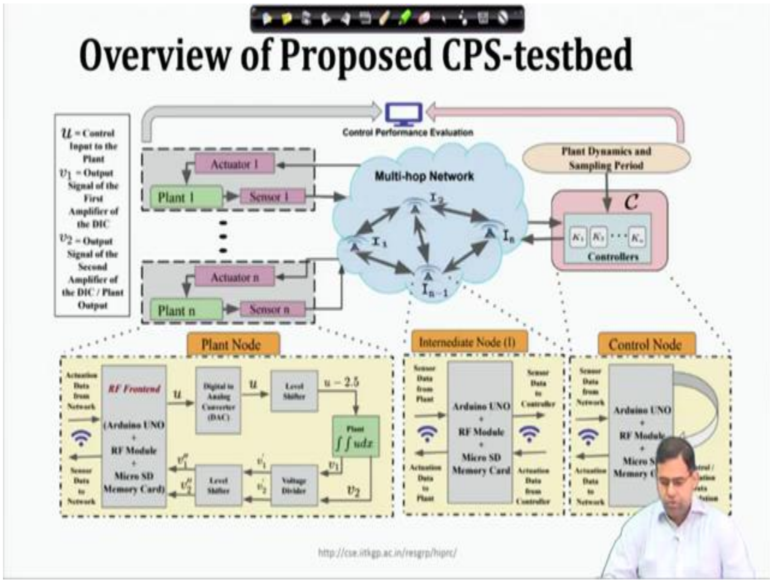

So, there are, there are several such applications where they can be used and we will. We will just talk about a sample example. So, suppose you are interested in making a very low cost CPS testbed, I mean you, you can do so much of CPS activity and learning using various simple elements. That is the point I am trying to make. So, we will teach you how to design ah things like what we call as a double integrator?

So that is an analog circuit which is by default unstable. It has to be given suitable controlled inputs to make it stable. So, it is possible to create such a double integrator like plant and it can be stabilized by suitable Ah control commands. ok So, let us say I create an Arduino based interface, so, let us say I have an Arduino microcontroller I attach to that Arduino microcontroller some radio frequency front end some some some transfer chip I am attaching and some memory card I may attach for data storage. ok This would have a digital output, so, I will need to attach some digital to analog converter here ah which may be part of the microcontroller board itself. And then I give it to this analog plant. Ok So, like I said this analog plant may be continuously needing this control commands to ah stay stable. Ah

One example I gave is the double integrator plant. It is very easy to build with two operational amplifiers. You can just try by buying those simple chips and and putting them on a breadboard. So, you can actually, control this thing and whenever the plants trajectory is, is changing position. Accordingly, you can sample the plant's measurements and so, ah so, so in those measurements can actually, be transmitted.

Those measurements can be saved here and those measurements can be transmitted through this network interface that I may have attached with this Arduino board to towards some central controller. So, let us say there are multiple such plans and there is one central controller from which I am trying to control and keep stable all these plants. So, how do I go about doing it so, these plants, like I said they will have a digital interface through this Arduino microcontroller?

So, let us say a control command has arrived. It will arrive through the RF interface. I have attached to the Arduino microcontroller and from there I will give the control command to the plant. The plants measurements will change. I will sample the measurements,. ok I will sample the measurements and OK here there should be a another two digital controller because here the output is analog. right So, from that output I will. I will take the digital value I will store it locally and I will also transmit it back to the network. Ok

Similarly, this thing can repeat there may be many other such nodes there can be I may not be able to transmit this back directly to the controller node because the controller node may be too far away. So, I will, I may have some intermediate nodes. They are also very easy to build. It is just an Arduino board with an RF transceiver module and maybe a memory card. So, this will receive the measurement and it will forward to some other node.

It will forward to some other node. This way it will go on and finally, it will reach the central controller. Now, this central controller is going to read that measurement. It will compute the control action and it will forward again it this thing to one of the nodes and this node will again hop back that value. Eventually, through this network it will reach the plant and it will stabilize it.

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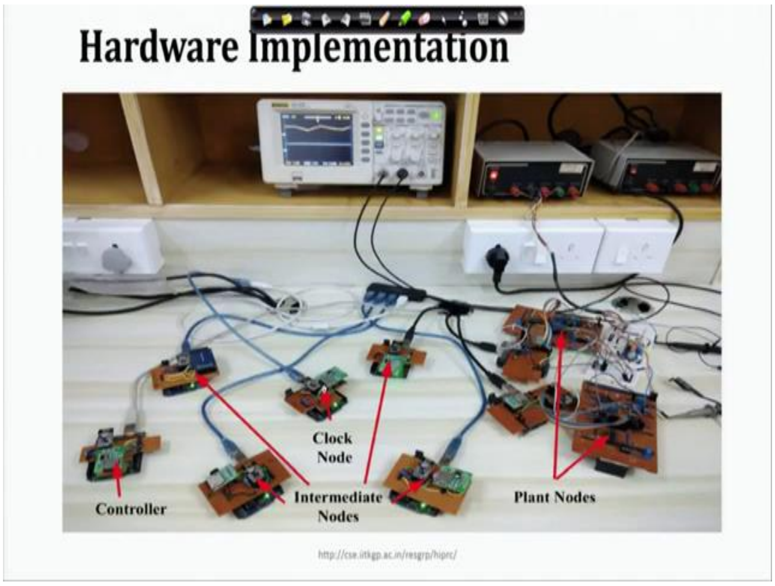

So, you see having such a thing may create lot of lot of issues. I need to route these messages through this graph in a suitable manner, so that those messages do not collide. right So, they must be. They must be transmitted in orthogonal time slots. So, I have to find suitable schedules for each message going from the plant to the controller and coming back from the controller to the plant using paths in this network which do not collide.

That means, at the same time two messages do not collide like that so that should not happen. right So, I have to avoid packet collision, not only that the roots chosen for each message. So, as you can see, there is a round trip involved in every sampling iteration, plant measurement should reach the controller control command should be computed and the controller should transmit back the control command through this network back to this plant.

So, this entire thing should happen inside one sampling period of the plant. We Will, We Will fundamentally define what is the sampling period on all that. Let us just think that it is a time period after after which the plants value is I mean, ah is just stored and transmitted OK and that is continuously happening. So, ah like this ah you have this sampling period as a time delay inside which this message moving back and forth should complete It is one round trip. Right

So that real-time deadline is to be satisfied without creating any packet collision for each of the different plants. So that is an important problem that how to design such real-time schedules for this network which you can solve and actually, you can see it is effect on this kind of a test bed. So, here you can actually, see these different nodes that we have created in our laboratory.

So, each of these nodes are nothing but Arduino boards, along with them I have attached one ah transceiver chip, it is a such transceiver. Chips are pretty low cost. I mean you can buy them for 100 rupees, actually. So, ah so, they will, they will just use the wifi wireless channel 2.4 gigahertz to do the transmissions. So, ah you can. I mean that is the that is based on the choice of chip I have made in this case. We wanted to have a very low cost testbed and these two bigger boards they are my plants.

So, they have circuits implemented here which represent double integrators and I want to control them. So, this is a full hardware implementation. You can have a simulation model of this. Also, you can just create that simulation model of such plants, such controllers, everything using your favourite programming language like python because python also provides the libraries of dynamical system modelling or if you have Matlab available to you, you can just do all these things in Matlab.

You can simulate the network, you can simulate the controllers, you can simulate the plants you can do this thing in Matlab. But these are entirely done in hardware. ah Because we wanted to have it as real life as possible. Now, ah well so, some of these nodes are the plants and there is this controller node. It is ah so, this wires that you see these are not for. ah I mean you can actually, see that these are not for sending messages here.

They are all I mean when this picture was taken. These nodes did not have individual batteries which is which is now there. So, these are just providing you power through from a common USB you have. OK Where the transmission reception are all happening through this nordic semiconductors, ah transceiver chip which is attached to each of these Arduino boards. So, what is happening is the plant message is getting transmitted to some of these nodes.

And it will get forwarded and it will be pushed to the controller and from the controller like you said, inside the time delay, the message must get back to the plan. So, this is just a picture we have taken and for that we have brought all the nodes together when we deploy them. What we do is we take each of these nodes, put batteries in them. And we can deploy them in pretty much far off places at different points inside our inside our building computer science in IIT Kharagpur and we can use some, you can.

We can have the plant located at a very remote place and it can be controlled through this kind of multi hop messages. ah We can even do something better we may have some autonomous cars. I mean we have not yet done that but there is definitely possible, like we showed those autonomous vehicle examples that we have created. We can and they have their real-time in they have their communication interfaces right.

So, ah we can we can simply use this kind of a network and multi hop nodes to relay messages to such autonomous vehicles ah and based on that the vehicles will be wondering about.

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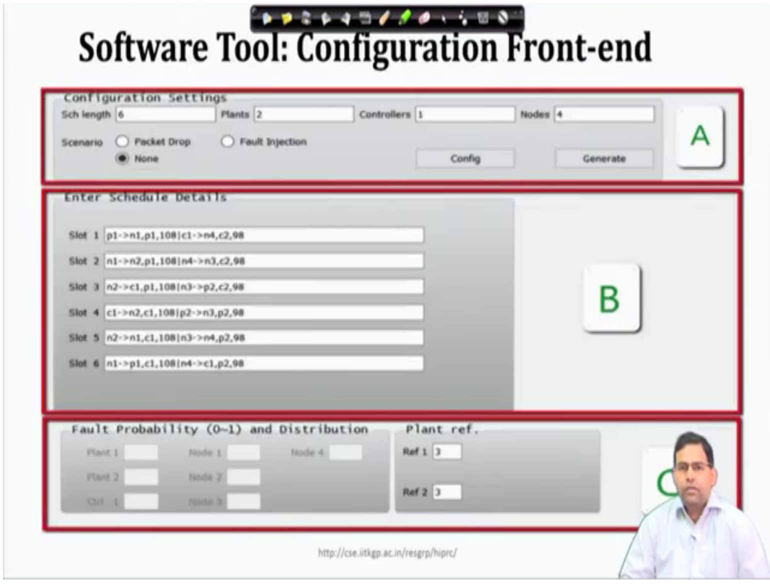

So, all that is supremely possible. Now, there are some niceties we have along with this hardware setup. For example, we have a GUI based tool. What it can do is I can design the network routing using this tool? So, I can specify that well, I can actually, give names to each of these nodes and I can create message transmission paths, like I said that the messages need to be routed through different paths.

So, this is a completely custom ah built software at our lab. So, what we are doing is, I am creating this routes for plant to controller message transmission and I am choosing payload size. I am. I am also choosing frequency channels, so, each of this transceiver chips. They actually, allow you to transmit your message using a set of possible frequency channels, so, we can actually, choose which channel to use and to transmit the message at what power level.

So, if it is a low power scenario, the the system is battery level is low. I can configure it to transmit messages at a lower power level but that will also decrease the reliability. Not only that I can actually redo retransmission because I can program this chip in such a way that it transmits one message for multiple rounds for added reliability. ok So, all these things can be done and all these things can be configured with the software.

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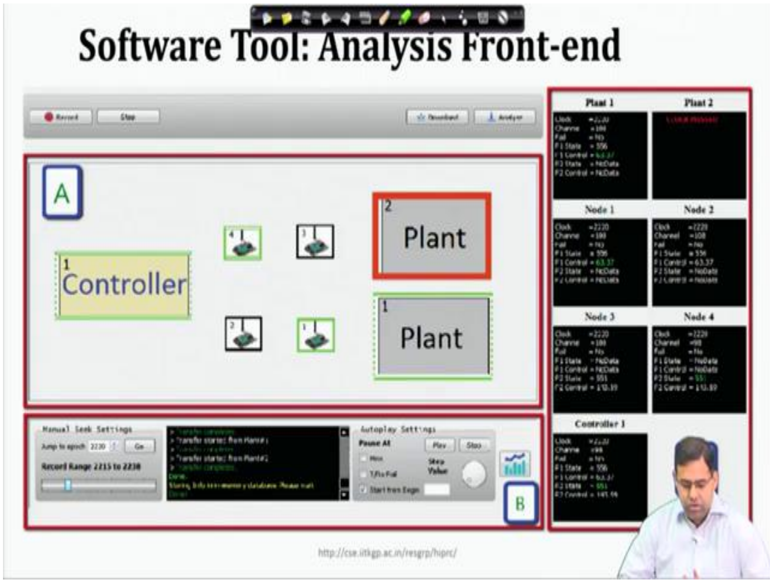

Now, once I configure this through the software, what happens is? This software will generate suitable programs which will be send over the air to each of these boards and each of these boards will now be enabled with suitable programs. So that when all the programs in all these boards run together, they will create the network routes for message forwarding. Like I discussed and those network routes, will have this property of meeting the end to end real-time, prop real-time deadline and also not creating an intermediate collision.

So, there is the good things that can be done here and this entire flow has been automated using a software tool that we have kind of developed here. So, it is very easy to make nothing nothing fancy here. If you are a computer science, computer science, somebody interested in computer science, it would be further easier or you would need to learn a bit of graph theory. And that is all and some amount of code generation technique ah to to actually, build such a tool ah not much of a big deal.

There are many other features. Also, for example, I can actually, run the system and let us say I simulate the entire setup for some amount of time. Then what will happen is each of the nodes will store some statistics about network transmissions. It will also store statistics about where, when some packet drops happen now I can actually, gather back all those statistics from each of these nodes.

Because if you remember each of these nodes also had some memory card. Right So, I will just click some replay button in this software and what it will do is it will instruct all these nodes to give back all the all the all the statistics. And after after receiving all the statistics in the central computer ah this software can actually replay the entire entire physi entire physics that happened. That means all the real transmissions, all the real receptions, all the real packet drops it can just keep on replying them. Ah

We can control replay speed and so many things here. And we can actually, see that where packet drops happen, ah where retransmissions happen, we can actually, see all those things. So that is the nice thing about the software and it can be really used for educational purpose for checking out ah how a wireless CPS works?

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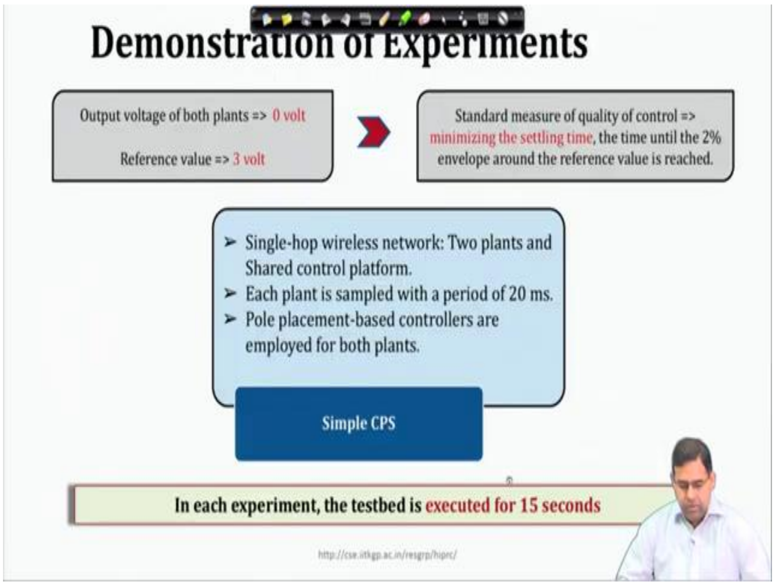

So, it can be used to create a simple CPS experiments. ah So, I am just trying to say that these things are available. These things are very easy to build and if you build such simple custom CPS models. Ah They are very nice ways to learn about real CPS issues.

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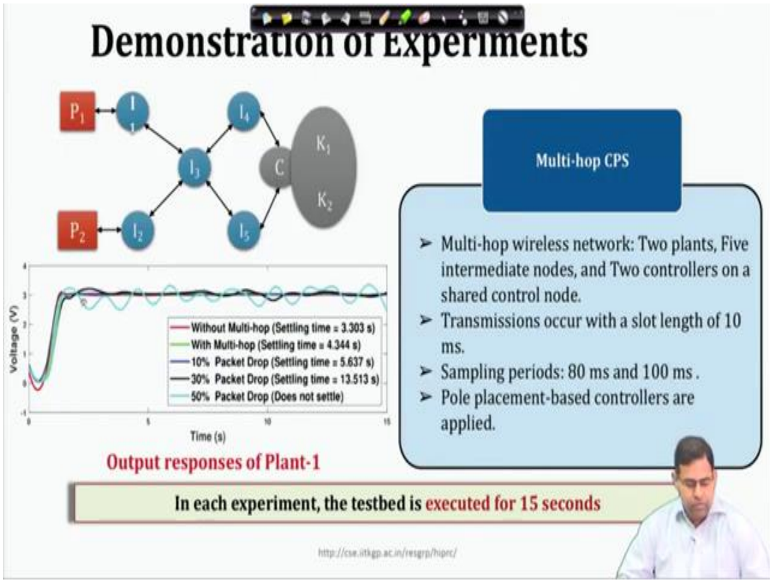

For example, I can do an experiment here, as if you can see that let us say I want to stabilize these plants right, they will be stabilizing around a reference value. So, if I am so, let us say I bring this, I mean I I physically attach the controller to the plants. That means there is no multi-hop then there is a settling time. ah That means there are not much of oscillations in the output voltage of this plants.

Now, if I, if I put in a multi-hop network, of course, there will be some network delays and all that. So, there will be an increase settling time. But now, suppose I am interested to know that suppose there are packet drops happening on the network. Due to such packet drops what is the effect on the system output? So, I can actually, configure that system to create packet drops. It is very simple right I in I I just make each of the Arduino boards to probabilistically not forward data.

I mean at some at certain certain ah trans reception transmission points you do not forward the data. So that is like creating a packet drop scenario and I can do it probabilistically. So, when I do that I can see what is the change in the output. So that is something happening from a physical setup which we can create at a lab scale. But if you are not interested in doing all this hardware that is fine, you can do the same experiment in a Matlab like environment or a python like environment, to see how things are working out.

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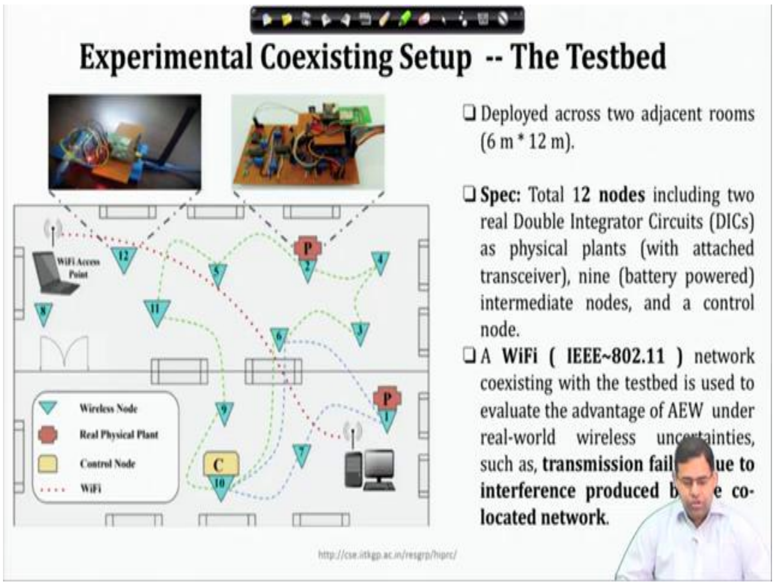

So, this is just for getting that extra feel that well, something really is happening. Now, it can be used like I said that this kind of a test bed can be deployed in a very in a in a in a large space across a building at different different points. right And you can actually, ah attach different kinds of plants, physical plants and not only that you can also have plants simulated. If you remember our previous examples of vehicle dynamics, we were simulating plants.

We can create Matlab models and we can actually, interface these Arduino boards with such Matlab models so that instead of controlling the real plant they may be controlling a simulated plant using these controllers which are running in this embedded processors. And the control commands between plants and the controller will be hopping through this kind of ah multi-hop network.

So, all that is possible and so and that that makes and doing this kind of experiments can can be very fun and it it may it, it may help you to gather more insight into building of real cyber physical systems. With this, we will be ending this lecture. Thank you for your attention.