Robot Motion Planning

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Lecture - 02
Joints and Degrees of Freedom

Hello and welcome to the second lecture of the course robot motion planning. In the last class, we had looked at the very basic introduction of motion planning where we discussed about path planning, motion planning and said that at the lowest level path planning basically means finding a path from an initial point to a goal point without hitting an obstacle. Now, it can get more difficult than that, for example, when you talk about a biped robot.

The biped robot not only has to find a path but it also has to traverse on the path. So, that is basically motion planning. So, today we will move on and we look at basic definition of robotics. Where did robotics come from? So, robotics is a subgroup of automation. So, we will talk about what is automation? Look at the history of automation. Then look at the history of robotics. Then we will talk about serial arms and mobile robots. What are joints? What are links?

And then, what is the degree of freedom? So, let us start off our second lecture by an introduction to automation robotics. And then, we look at joints, degrees of freedom and linkage. So, we will start off today's lecture with the origin of robotics; where robots came from? Where are we at present? And what is the future of robotics? Then, we will move on to the structure of a robot both for a serial arm and for a mobile robot.

Now what is the link? What is the joint? How many degrees of freedom are there? What do you mean by degree of freedom etcetera?

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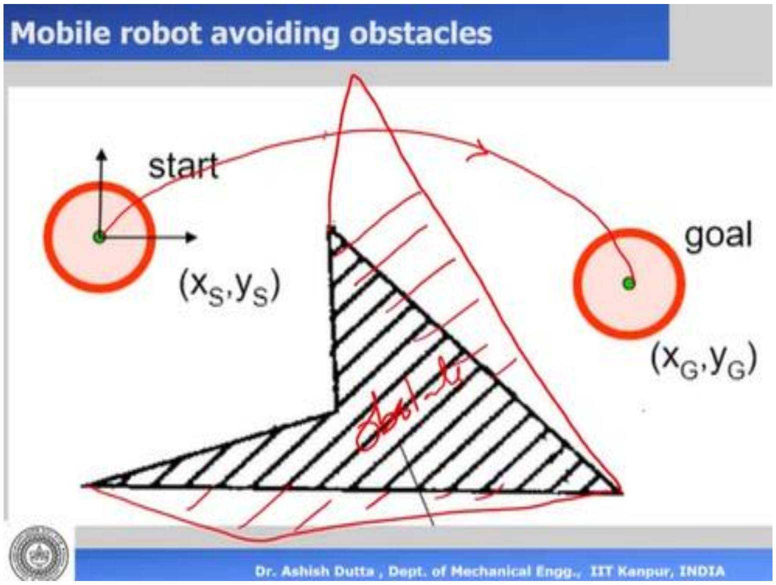

So, in the last class, going very briefly into; what we were doing? We talked about robot mobile, robot avoiding obstacles and going from a start point to a goal point. And this is the very basis or the very basic concept of robot motion path planning. This means that we have a start point and we have a goal point. And this is a circular robot to make life simple and there is an obstacle which is here. So, this is my obstacle.

And the fundamental of path planning is to find a path that will take us from this point to this point without hitting the obstacle. How many paths can there be? There can be very large number of paths. And, we also have to answer the question if there is no path, for example, if the obstacle was very large. For example, the obstacle was this big the obstacle was something like this. Then, a path does not exist between start point and goal point.

In that case also, the path planner must be able to tell us that no path exists. So, at the very basic level, this is the definition of our path planning problem.

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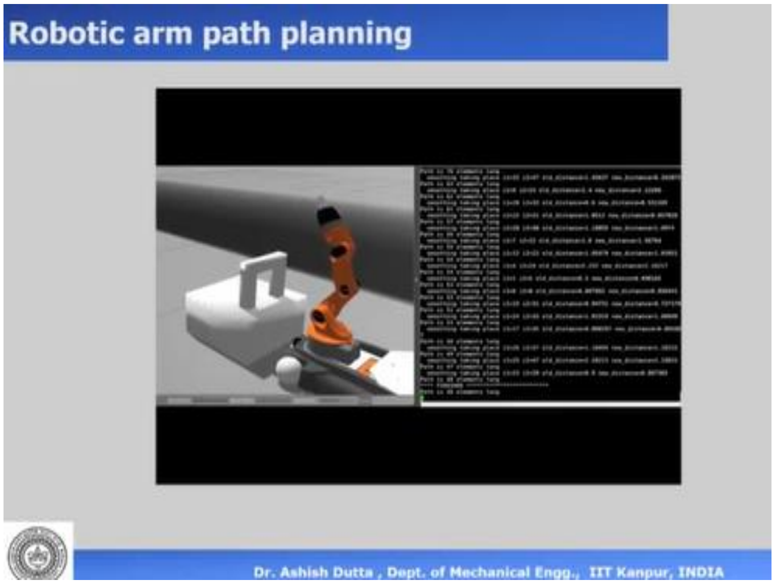

Now, this is for a mobile robot as we have just seen. Now we can also have for a serial arm. This is the example of a serial arm which I showed in the last class where the serial arm robot must take its end effector and put it through this U-shaped a hole there. So, it should be able to configure itself such that it can put its end effector and go under that U-shaped kind of an object. Now this is path planning in the case of a serial arm.

Again, the same question; does a path exist? If a path exists, how many paths are there? Then the next question would be finding an optimal path. Optimal in terms of time, in terms of path length maybe, in terms of energy. So, this is the case of a serial arm. The previous one was case of a mobile robot.

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Now, it can get more complex than this, for example in the case of a biped robot. Here also we have a biped robot which is walking. Now this has very large number of degrees of freedom, 54 degrees of freedom. We will shortly come to what is the degree of freedom. And the robot has to walk from one point to another point without hitting obstacles. In this case, why is it more complex? Because you cannot define an obstacle. What is an obstacle here?

For example, is a tree an obstacle? Or is the hump behind an obstacle? For example, that is here, this hump is that an obstacle? Is the tree an obstacle? How do you define? So, it can get more complex than the very simple statement of it should go from one place to another place without hitting an obstacle. So, in this case, we saw that there are very large degrees of freedom.

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And the robot has to find a part to go from one point to another point without hitting obstacles and maintaining its own balance. And this is basically a question of motion planning. So, it has to not only find a path it has to also go on the path. And while going on the path it could have various kinds of constraints. For example, there could be kinematic constraints. There could be balance constraints. For example, the robot should not fall down.

So, that is a constraint now in the system. So, this is a more complex problem. And so, we can go from a very simple problem to a very complex problem as we go along this course of robot motion planning.

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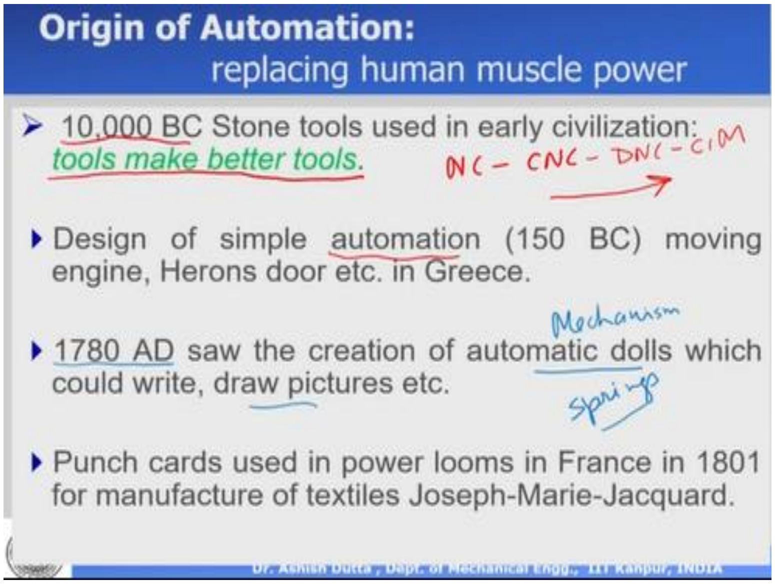

Before we move on further, let us look at what is a robot? Where did robots come from? Now, we know that robotics is a subgroup of the larger field of study which is automation. Now, what is automation? Automation is basically replacing human muscular power. So, you can have office automation. You can have factory automation. You can have industrial automation. You can have home automation.

Wherever you are replacing human muscular power by either using some kind of automatic device, for example, a vacuum cleaner or some other mechanism which is doing particular tasks. Then, we say that is automation. And this business of automation has been going on for very, very long time. It is not like somebody invented automation one fine day. And from that day, we have automation it is not like that. So, this process has been going on for a very, very long time.

Very long means right from 10,000 BC that is thousands of years and robotics is a subgroup of this larger field of automation. So, we have lot of other things like hard automation. We have software automation. We have CNC machines, NC machines. They are all automation. So, robotics is just one part of that. Now if you look at the process of automation this has been going on for 1000 of years.

Say right from 10000 BC, human beings were using stone tools to make life easier. So, we made stone tools then we have iron tools and copper tools in that order. Now very interestingly, tools make better tools. And that is the way civilization is progressing. And this is a part of automation. We are automating by using tools and tools are making better tools. This is very interesting statement because from an NC machine we have a CNC machine.

Then from CNC we have DNC then we have same. So, it is basically going in that direction. Tools are making better tools. We have robots, we have better robots. Today, we have autonomous robots and intelligent robots 10,000 BC, we have different kind of tools to make life easier. Now design of simple automation was there around 150 BC for example, the moving engine and Heron's door.

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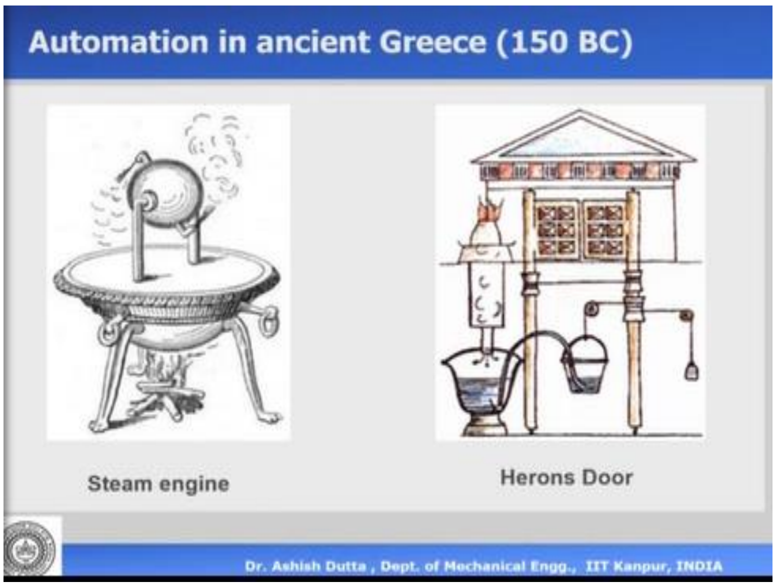

So, this is an example of the steam engine. Now you can see that on the left hand side, we have the steam engine. And how this works is there is a container containing water and fire is burnt below the container. So, there is fire which is burnt. Now this fire heats up the water and produces steam. And the steam comes out through these two pipes and comes out from this nozzle and that nozzle. Now, you can see that they are pointing in different directions.

So, because there is an axis here of this hemisphere and because the steam coming out of the nozzles will impart a force and there will be a resultant moment in there. And this will start rotating the hemisphere will start rotating. And this is the earliest example of a steam engine. Now, if you look at the date it is 150 BC. This is the earliest example of what we see automation. Why automation? Because something is moving without human muscular power.

Hence it is automatic. On the right side, we see the example of Heron's door. Now in this, you can see that, how this works is they would burn fire again here. And the fire will increase the pressure inside this container. And once the pressure is increased what would happen is, it is going to force this pressure inside the bucket will increase it will force the water down. The water will go through the pipe and then flow on to the other bucket there.

Now, as the water level in the second bucket increases what will happen? The force this side will come down it will increase and the pulley is going to rotate. So, the pulley will rotate like that. Now when the pulley rotates what would happen? The door is going to open. Now if the door opens this is an automatic opening of the door. You put up the fire and the door closes. So, this is an example of automatic opening and closing of door which is basically automation.

Now again, if you look at the date 150 BC so this is very, very long time ago. Now 1970s we move forward saw the creation of automatic dolls that could write and draw pictures. These are very small mechanisms. Now, we can call them automatic dolls. We can call them mechanisms. And the energy input was basically by means of springs, like in old watches. So, you have to wind the spring and the spring will store the energy and give the energy to this mechanism to move.

So, this is about 1780. Now about 1801, this gentleman Joseph Jacquard in France made the power loom which was an automatic device.

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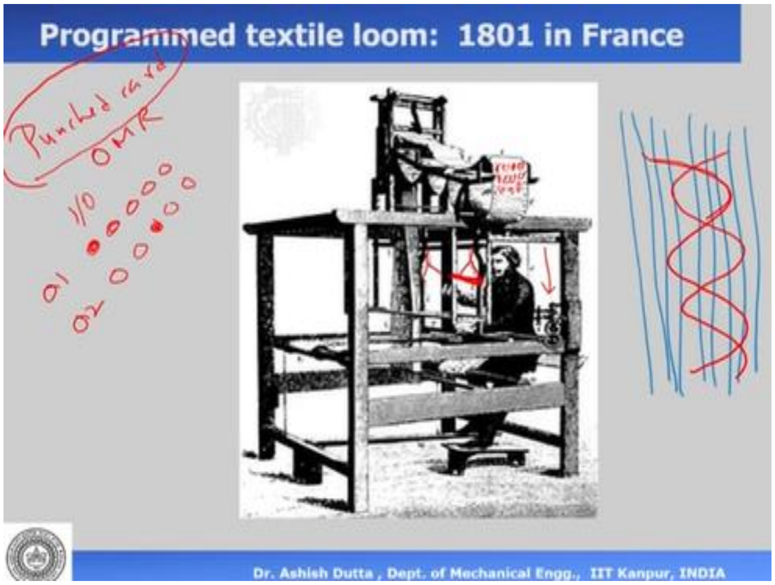

Now, what he did is, this is a textile power loom. I am sure you would have seen this power looms which are used in the villages even today for making textiles. And how this works is basically? There would be threads which will be running like this. So, these are threads which are running. And to make designs on this thread the person would be having another colour thread, for example red colour and the person wants to make a design like this.

So, what the weaver does is you can see the threads here coming like that. So, the weaver would change the position of this red thread as it is running through the blue threads. And how would they do that? They would move a lever. Even today you can see that the person, that the textile weaver, basically catches the lever and changes the position of the threads. Now what this gentleman did is he encoded this design in the form of a punch card.

Now this punch card is very similar to the OMR sheet that you are very, very familiar with these days. So, this OMR sheet has basically bubbles. So, for example, when you are answering questions in all kinds of exams, the objective type questions. So, you would have a hole like this and you can give your options by marking the hole or not by marking the hole. So, now, you have question number 1, question number 2 with this many choices.

So, whatever is your choice you can darken it. And the machine can read this. How does the machine read? The machine can basically see whether it is black or white. So, it is a 1 or a 0. So, this is what this gentleman did. He made a punch card. And he embedded this design in the form of a punch card. So, there would be holes in there, holes or no holes. And the machine could read this.

And basically, he embedded this design in the form of this punch card and the machine could read this punch card. Now this is the earliest use of a punch card. Now the older computers, NC machines they all use punch card for when you are writing the program in the early days. They would write it in the form of a punch card. And there would be a hole or no hole and the card reader can read that.

So, the earliest example of a punch card or of a program which is written for a machine to read is 1801 by Joseph Jacquard in France in the form of a power loom.

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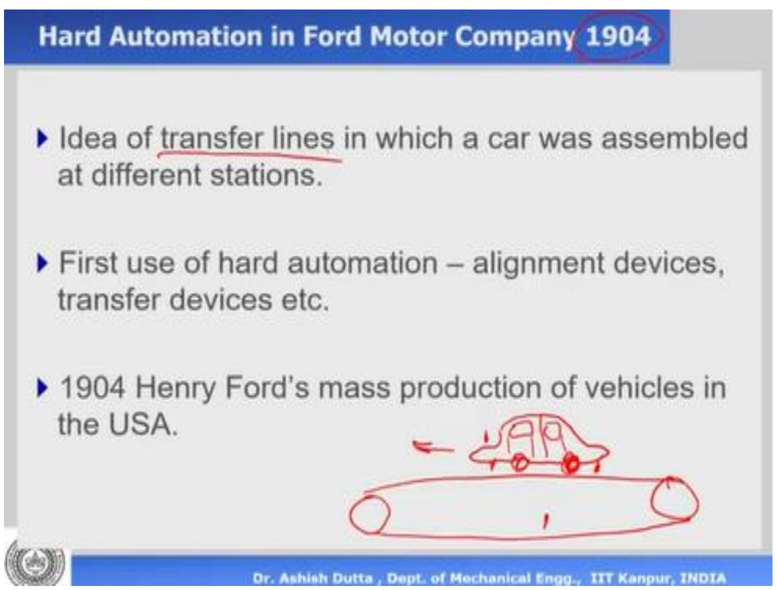

Now as we go further, the idea of transfer lines for assembly of automobiles was invented somewhere around 1904 in the Ford Motor company in the US. And even today, if you go to any automobile company you see that the way cars are assembled or the way cars are manufactured. There would be a car sitting in a conveyor so we have a conveyor. Let us say this is a conveyor, and there is a car. The conveyor is rotating and there is a car body.

And there is a car which is here so that is my car. And that is my car, these are the wheels. So, the car is going to be sitting or will be mounted onto the conveyor. And it is going to move. And at different positions it is going to come and stop. There would be a person or there would be a robot which will do particular operations on the car. For example, at this location, the wheels may be fitted. In a different location maybe, the glass is fitted.

So, this idea of a transfer line as the name indicates transfer lines this car is being transferred from one position to another position was first invented in 1904. And this is basically what we call hard automation. And this uses alignment devices, transfer devices to move from one position to another position. At every position, something, some operation would be carried out on the car. Now, this is basically what we call hard automation. Obviously, there is no robot till now.

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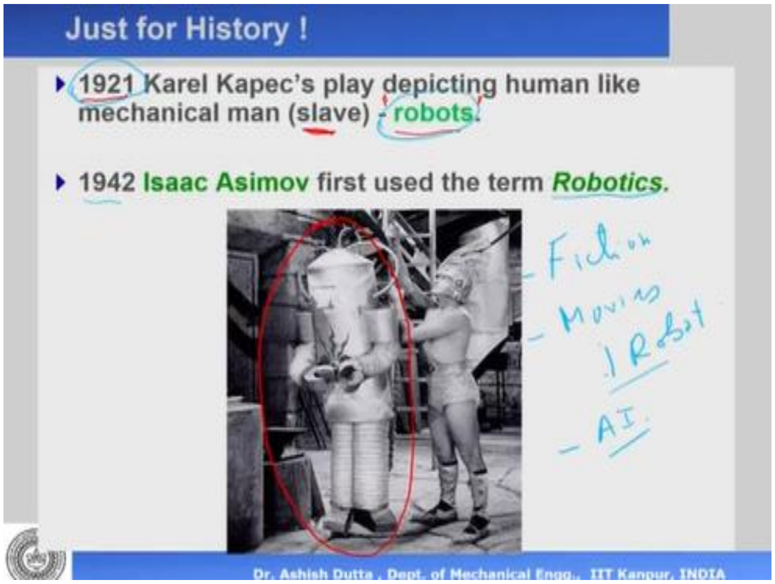

Now, where did the robot come from? Because we are going to look at robotics in this course. So, in 1921 this gentleman Karel Kapec, he wrote a play depicting human-like mechanical men. So, he was a Czechoslovakian playwright and he wrote a play in which he said that in future there will be mechanical men or what he called slave who will be replacing human beings in industries. So, this is apparently a picture from this play.

So, there is a mechanical men who is replacing human beings to do dirty jobs so mechanical man or mechanical slave. So, the word robot basically comes from there, 1921. Of course, there are no robots till then at that time. So, 1921 the word robot came from his play as written by Karel Kapec. Now 1942, Isaac Asimov first used the word robotics, where he said that in future there will be a subject called robotics. He also laid down the three laws of robotics.

And then, he wrote a lot of science fiction. Today, there are a lot of science fiction books which are very interesting. There are movies today, for example, I robot. I do not know how many of you have seen that. And he has written for maybe what life would be like even 200 years from then. And very interestingly lot of that is coming true. So, it is very interesting to note that 1942 there is no robot.

But this gentleman could imagine that in future there will be a subject called robotics. And there will be robots and they will be behaving like this. He also talked about AI, about intelligence and the robot would have some amount of intelligence. So, just for history, the word robot came from here. And the word robotics was invented by or first used by Isaac Asimov in 1942. Of course, at that time, there was no robot.

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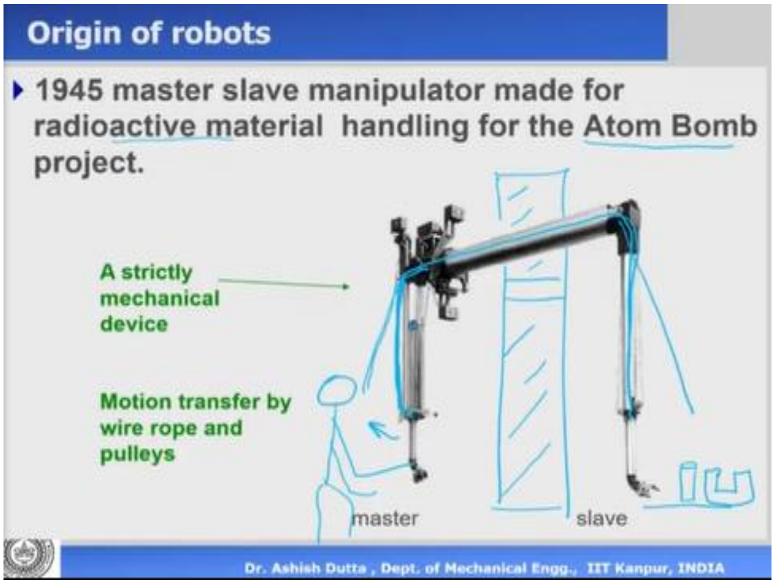

So, where did the robot come from? So, in 1945 during the Second World War, they were making the atom bomb. And in the atom bomb project, they had to handle radioactive material like uranium and plutonium where human beings could not go near because of radiation. So, they made this device, this mechanical device called a master slave manipulator. And how it works is you have a master and you have a slave arm and they are both identical.

And in between, there is very heavy shielding. So, for example, there is a wall with a very small window here. So, if you want to handle something, for example, you want to lift this object and assemble it inside this hole. What would be done is there would be a master would be standing here or the operator stands here and holds the, so the operator is standing here and is holding the master arm. And this master arm has joints, revolute joints.

And each joint is connected by wire rope and pulley to the corresponding joint. So, something to note the master and the arm are same in terms of kinematic structure. So, how many degrees of freedom it has this also has that many degrees of freedom. And the motion transmission is by wire ropes and pulleys. So, if the operator pulls it in one direction, so pulls it in this direction, what will happen?

The tension here will change if the tension changes here the tension here will change. So, if this moves like this, this will also move like this. So, this is basically showing that motion transmission is by wire rope and pulley. And very simple motions could be done like pick up this object put it inside here. And there is an open close of the gripper there. Something to note is that this is strictly a mechanical device. That means there is no electronics here.

There is no sensor actuator controller. And motion is transferred by wire rope and pulleys. And this is used even today in various atomic energy establishments across the world. And, this is the father of the robot. It is basically a mechanical device. But you can call this as the father of the robot 1945. Now 1948, something was invented, 1948 - 49, that changed mechanical into electromechanical.

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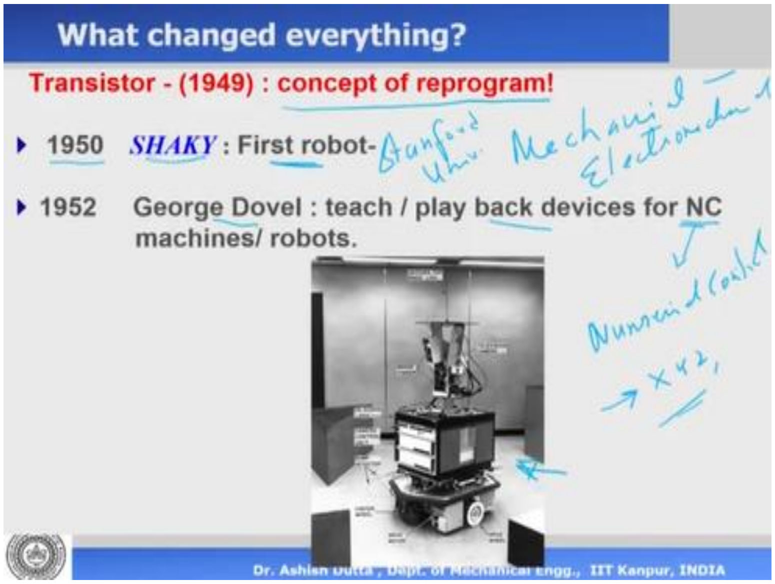

So, what was invented in 1948- 49 is the transistor. Now with the transistor came the concept of reprogram. We have a computer we have a microcontroller we have microprocessor. All these came over that time after the invention of the transistor. And with that you could have the concept of reprogram. Now here, this is a mechanical device you could not reprogram it. Once you make it is fixed.

But after you make the transistor and we have a computer you could change the program and the device could behave differently. And the concept of reprogram came about 1949 and mechanical became electromechanical or what we even call mechatronics. So, you had the fusion of mechanical engineering and electrical engineering and you could reprogram mechanical devices. And they could do different tasks depending on their program.

So, 1950 the first robot shaky was built, in Stanford University. At Stanford the first robot which is shown here which is called shaky. And it was a very simple mobile robot which could just go from one point to another point in the world obstacle that is it. In 1952 we had George Dovel with his patent on for teach and playback devices for NC machines. So, a robot and NC machine is fundamentally the same the motion control is the same.

They are both controlled by programs. In a robot, we have a program which is controlling it and it is going from one point to another point. In an NC machine, it is again a program which is controlling it, which is performing particular tasks. So, this NC basically means numerical control. Numerical control or controlled by numbers. So, we are inputting x y z coordinates and it is following those coordinates.

So, fundamentally the controls of both are the same or robot and an NC machine. So, we see historically where the robot came from. Now, there were three major inventions which changed engineering. So, the first invention was the invention of this transistor 1949 from which we had electromechanical systems coming up.

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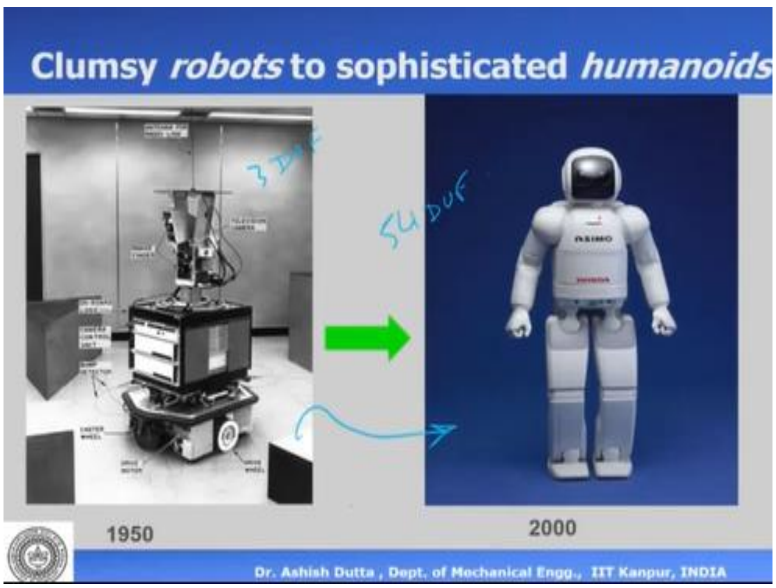

And so, for the last 50, 60 years or 70 years. Now we see that the robot has gone from a very simple device to a very complex device. This probably has 3 degrees of freedom which can just move around. This one has about 54 degrees of freedom. It can walk, it can run, it can talk, and it has vision. It has speech recognition and all kinds of other tactile sensors. If it falls down it can get up. So, from very simple system to a very complex system which has gone in only 70 years.

So, there were two more inventions that resulted in the robot going from here to here. The first was the invention of the transistor because of which we had the robot.

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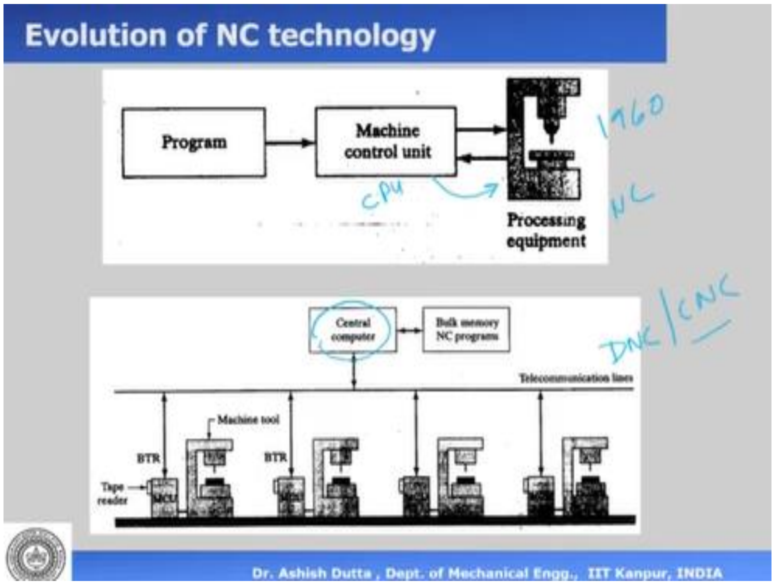

Now, as technology progressed basically the computer became more powerful. And these machines or mechanical machines they progressed because the computer technology progressed. And what I mean by that is the computer became smaller it became more powerful. So, in the early days 1960s, you had one program, one machine control unit meaning a CPU, for example, it was controlling one machine that is basically what we call NC.

Now, as the computer became more powerful, we had one computer which could control many machines now and we have things like DNC, CNC. So, as the computer became more powerful, we could control more number of machines. And this is how it progressed.

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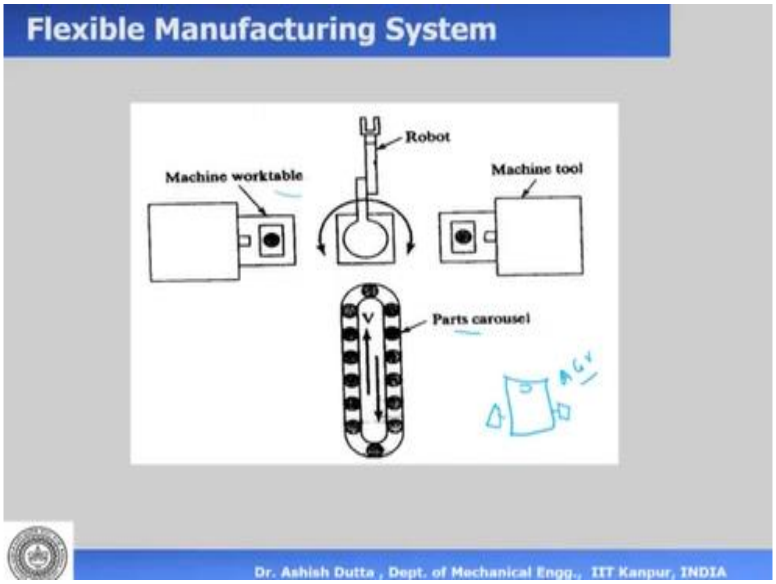

Now, it could control not only different machines it could control different kinds of machines. For example, flexible manufacturing. The computer could control a robot, a work table, a parts carousel, a part transfer device. You could also have an AGV for example we have an automated guided vehicle here, which is scanning parts. So, we have an AGV here. So, the computer now can control all of these devices together. It became so powerful.

And we can see that how the automation technology progressed. Now it became more powerful. So, this is about 1970s.

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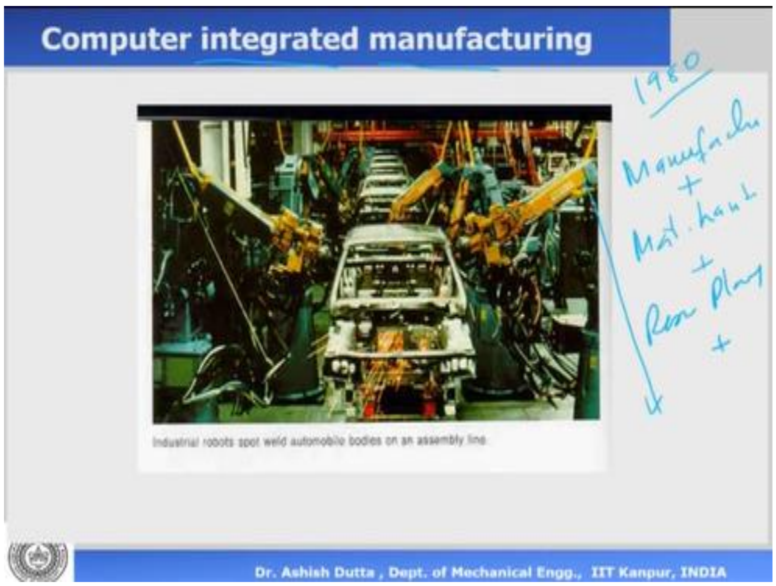

Now, it became more powerful and we have computer integrated manufacturing. Now, what is computer integrated manufacturing? That is basically the computer is not only looking at the manufacturing. So, it is the manufacturing plus material handling, say, plus resource planning. All other activities that are there are being controlled by the computer itself. So, it is like computer integrated manufacturing.

It is not only the manufacturing but it is integrating manufacturing with other like resource planning, planning, scheduling all these are being integrated by the computer itself. So, it is essentially that the computer has become more and more powerful.

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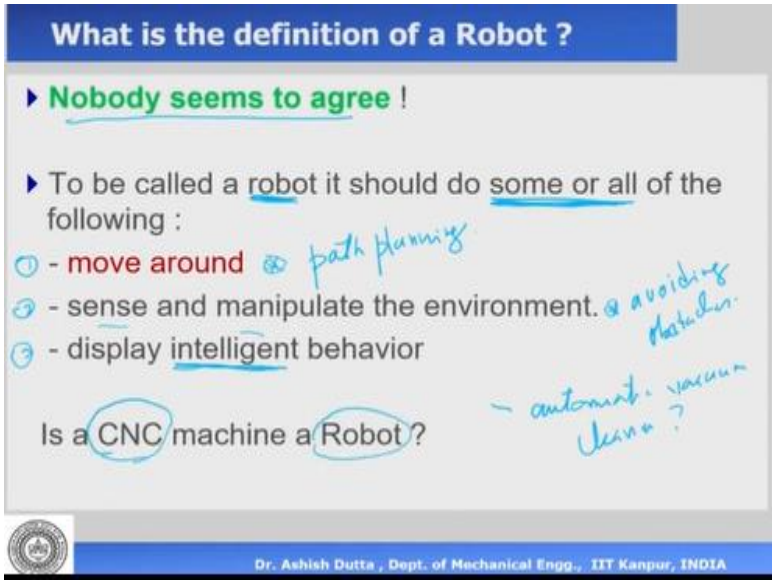

So, this is about 1980s. Now, we had robots around 1960s onwards in industries. They were basically doing industrial tasks like spot welding, spray painting, pick and place. Now what is the definition of a robot? Now that is interesting. Interesting because nobody seems to agree, why? Because everybody I mean students would like to say they are working on robotics. Industries would like to say their product is a robot, it sells better it sounds better.

So, everybody would like to call their product a robot. So, what is a robot actually? So, nobody seems to agree on that. That is interesting. But it is generally agreed, that to be called a robot a system should do some or all of the following. So, a system should do some or all of the following. Following what? number 1. Should move around. So, fundamentally a robot moves around.

And hence the question of path planning, motion planning, comes from here that the robot should move around. And for which you need a path and you need a motion plan. So, we can say path planning fundamentally because a robot has to move around. So, the first requirement of robot is that it should move around. Second is, it should sense and manipulate the environment. Sensing it should have some kind of sensors, for example, ultrasonic sensors to avoid obstacles.

And in manipulating the environment, for example, it is picking and placing an object that is manipulating the environment. So, sensing like for example, avoiding obstacles. So, this is avoiding obstacles. It is a sensing and manipulating the environment. Number 3 is displaying some kind of intelligent behaviour. So, let us call this number 1, number 2, number 3. So, it should display some kind of intelligent behaviour.

For example, at the crudest level, you can say that ok avoiding obstacles so it has some kind of intelligence may be to avoid obstacles. But this word intelligent is very often quoted in all kinds of contexts without really meaning what is intelligent. So, we basically say if a system can deal with unknown, unforeseen or corrupted data then it has some kind of intelligence in the case of robotics.

Because lot of the data that you get from the real world will not be exact because there will be errors in there. So, how do you deal with it? That would require some kind of intelligence. But at the lowest level, we can say that a robot has intelligence if it can plan its action by itself and do some tasks by itself. So, by this definition, if a system can do any or all of this, we can call it a robot. So, is automatic vacuum cleaner a robot? Yes, it is a robot.

Why? Because the; automatic vacuum cleaner can clean and plan its path and do things by itself. So, there are vacuum cleaners which are automatic these days. They can function by itself. Now is an intelligent wheelchair a robot? Yes, it is. Because it can find its path; and go from one point to another point without hitting obstacles. So, in that sense it is a robot. And when the real vehicle yes it moves around it is a robot.

What about a CNC machine? Is that a robot? Well, no because? CNC machine does not move around. It does not sense and manipulate the environment. And it does not display intelligent behaviour. So, that gives us a basic definition between a machine tool and a robot. So, please remember this that there is no formal definition of a robot. The earlier definition was multifunctional manipulator.

But that is not valid anymore. Because we have things like drones, we have underwater vehicles and all of these are not manipulators. So, we can say a system is a robot if it can do some or all of these 3.

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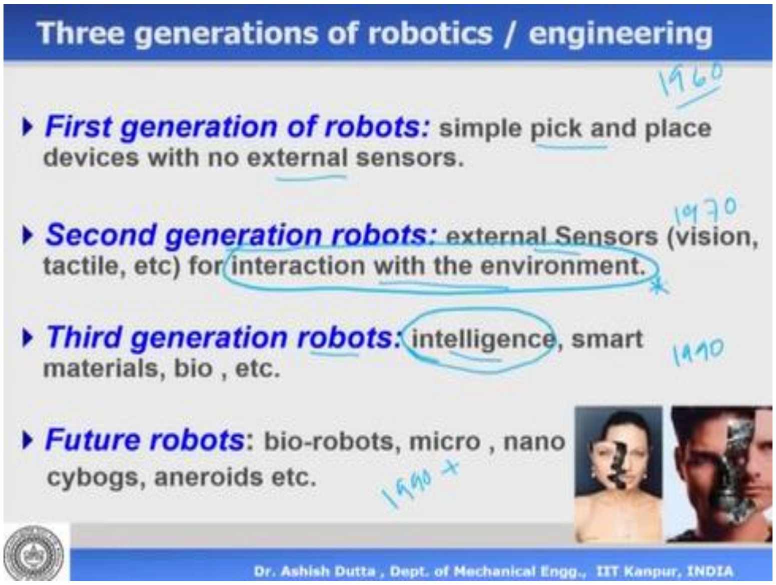

Now, since 1960s, we have had three generations or four generations of robotics. The first generation of robots is basically simple pick and place machines with no external sensors, which are used in industries. Second generation, about 1970s, is basically they have external sensors like vision tactile force stock sensors for interaction with the environment. They are second generation of robots. Third generation is basically what we call intelligent robots.

They are basically made of smart materials. We talk about bio robotics, micro robotics nano robotics. So, this is about 1990s. And then we talk about from about 2000 plus onwards. We talk of bio-robots, micro robots, nano robots, cyborgs and all those. So, this is basically the progress of the various generations of robots that we have. Now something, you will note here is that the differentiation is basically interaction with the environment.

This is the catch word here, an intelligence, intelligence and interaction with the environment. So, if a robot can interact with the environment properly. Then we say it has some kind of intelligence, and it can plan by itself. So, these are two catch words. One is interaction with the environment for which you need all kinds of sensors. And the other is the third generation robots which are supposed to be intelligent.

That means they can decide certain tasks by themselves. How did we go from the first generation to the second generation?

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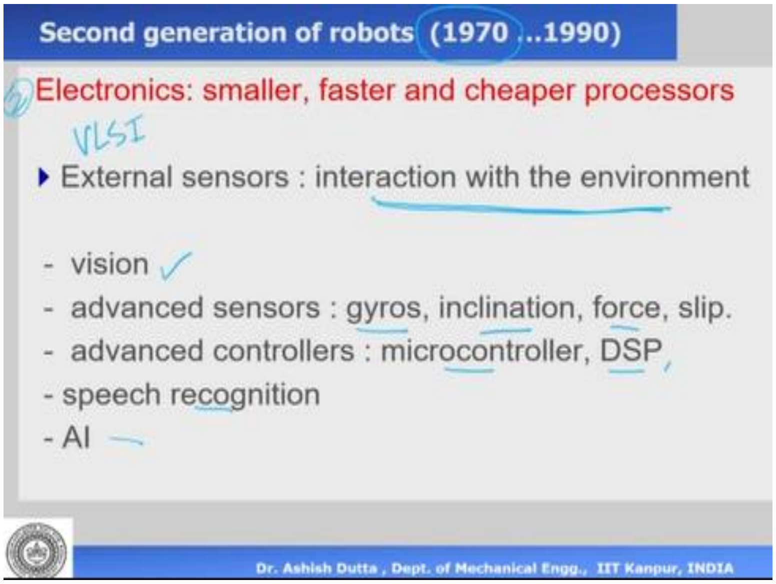

There was the invention of the VLSI. So, essentially, we had VLSI which was invented somewhere in 1970s. So, very large scales integrated circuits. What VLSI enabled is that the electronics in the form of diodes, triodes and vacuum tubes which was there in the early days of the computer they all could be made small and could be fitted onto one motherboard. And that is very large scale integrated circuits.

And because of which electronics became smaller, faster and cheaper. And you had cheaper processors, you have cheaper cameras, you have cheaper sensors. They are not only cheaper they are faster and they are smaller. And this you know today that you can buy a web camera for a very, very cheap price. A good camera you can get for 500 rupees or 600 rupees of very good quality that you could not get in the early days 1967.

So, it is not that the camera was not there the camera was there but it was so expensive. It was so big in size that people could not use it. Now once electronics became smaller, faster and cheaper you had small cheaper processors like microcontrollers, microprocessors. Then you had different sensors like force stock sensors. Then you had computer vision coming in, cameras coming in and with this you could have better interaction with the environment.

And we started off having applications of these in robotics in the form of vision. You started having robots which are guided by vision advanced sensors; gyros, inclination sensors, force stock sensors. Advanced controllers; microcontrollers, DSPs, FPGAs. We have subjects like speech recognition, AI coming in. So, AI came in robotics in a big way about 1970s. Because essentially, we had smaller processors and faster processors that could be used on robots which was not possible earlier.

So, this is the second generation. So, the first great revolution was the invention of the transistor. The second great revolution is the invention of VLSI where electronics becomes smaller, faster and cheaper. And even today, we can buy electronics has become so cheap and fast and small that you can embed that in your mobile phone, in your cars, in your clothing, in home applications like washing machines.

And you know that we have cheap processors like the Arduino processors which hardly cost 500 rupees. But are extremely fast and can do very good control applications. So, this is the second revolution that took place.

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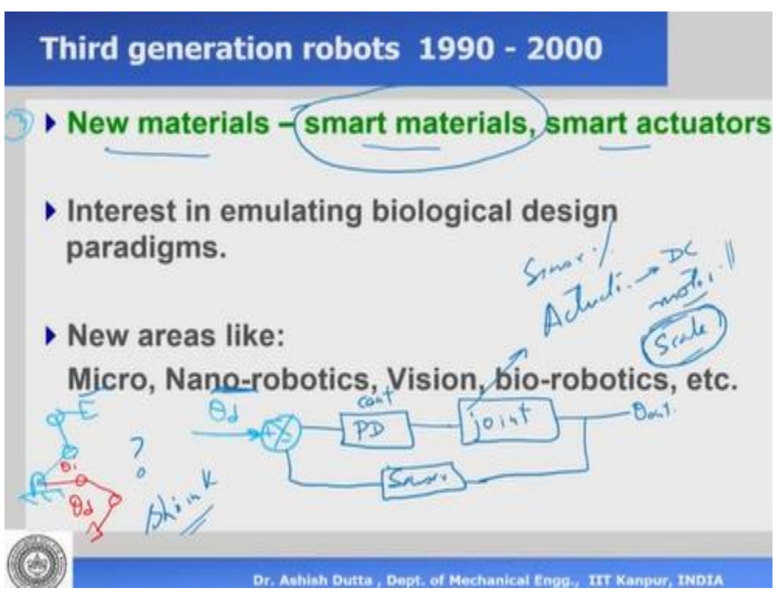

Third is new materials. So, the third is here. Now it is very interesting to note that a conventional robot would have, let me draw it here. So, this would be the conventional robotic control structure. So, there is a plus, minus. This is my θ_d. If it is a serial arm and I want the arm to move, from one point to another point, so, it is here. And I want it to go to some other location, I want it to go here. I want it to go like this.

So, this my θ_d and this is my θ_i. So, there is a plus minus there. That is the summing block in my control system diagram. Then we have a controller. So, let us call it the PD controller here, so, this is my controller. That is my robot link. So, this is my joint, the robot joint. And then I have feedback and we have some sensor here. So, this is the basic control system diagram for the link of a robot so, this is my θ_o.

Now, if I want to make a small robot, for example micro robot, nano robot how small is small. So, small that can go inside the blood vessels, micro robot is very, very small nano robot is even smaller. You want to have advanced applications like bio robotics, advanced vision control robots. So, in that case, if you want to make a micro robot, I take a big robot and I make it small, I want to make a micro robot so what do I do? I take a big robot.

I take this arm robot for example. I shrink it, I make it small. Now you cannot shrink something, why? Because we have an actuator here. We have an actuator there which is basically a DC motor let us say. Now, if you want to make it smaller and smaller and smaller after a particular scale this DC motor will not work, you know that. Why? Because it will not provide enough torque to move the system.

Because if you make the; motor smaller the magnets are becoming smaller. So, their strength is decreasing so the output torque is also decreasing. So, this concept of going to the micro and the nano scale by simply shrinking something from the macro scale does not work. So, you have to use actuator sensors which are different from the conventional actuator sensors. Different from the conventional means you cannot use DC motors AC motors.

You have to use something else because you are going to the nano-scale now. And what is used is essentially actuator sensors made from new materials, what we call smart materials. And these are called smart actuator smart sensors. So, the third generation of robots is essentially the invention of or the use of new materials for actuation sensing. And we have robots which are made not like the conventional motors with conventional motors encoders but with smart actuators like Pezos, crystals, electric polymers etcetera.

And these are robots which can go in the micro domain and the nano domain. So, there is something called the scale effect or the size effect. And this is interesting that you cannot simply shrink something and make it small it, does not work like that. Now with new materials, smart materials, we could make robots which can work at the very small scale. And this is the third revolution which took place was the invention of smart materials-based actuator sensors.

And we had new robots in the area of micro robots, nano robots etcetera. So, this is the third generation. Today, we are in the fourth generation which is basically what we can say the futuristic robots or future robots. And they are all kinds of robots, for example, bio-robots, the androids, cyborgs and at the micro scale, nano-scale we have medical robots we have exoskeletons. So, today, we are in a scale where biology is also getting integrated with robotics.

But the same issues of path planning, motion planning still remain. So, this basically gave us an introduction of robotics; where robots came from? Robots is a part of automation and we have seen that robotics basically came with the invention of the master slave manipulator. And then it became electromechanical with the invention of the transistor. And then we had these 3 revolutions transistor, VLSI and new materials that is where robotics stands today as we are going towards the future.

Now, something to note is that a robot has to move around. So, basically it means that you need a path plan. To move you need to have a path and once you have a path you have to go on the path that is your motion plan. So, let us move on now.

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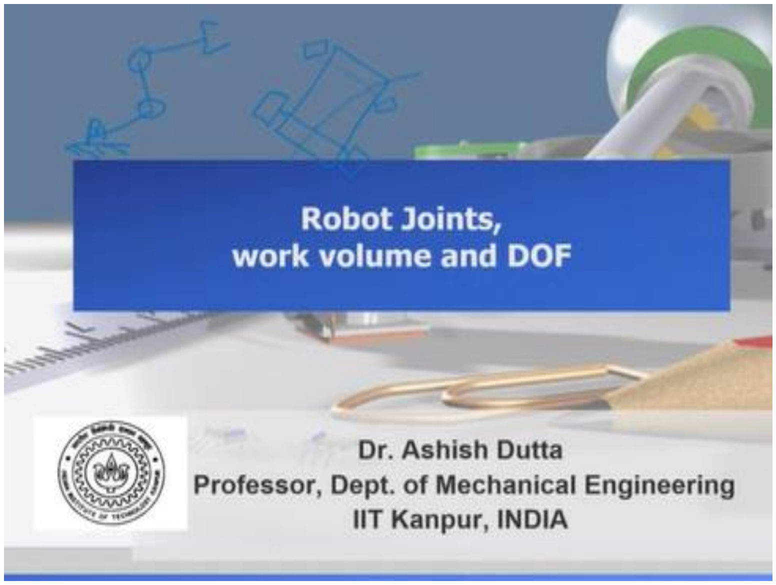

So, we will start off with looking at the fundamentals of robot joints, work volume and degrees of freedom. So, we will talk in terms of serial robots which is an armed robot it is a serial arm. So, this is a serial arm. It has joints like this and there is an end effector at the end the base is fixed. We can talk in terms of a mobile robot, for example, we have a car kind of a mobile robot here which has two wheels, two wheels are there and there is a steering wheel here, so, this is a steering wheel. And it can have a particular trajectory like that.

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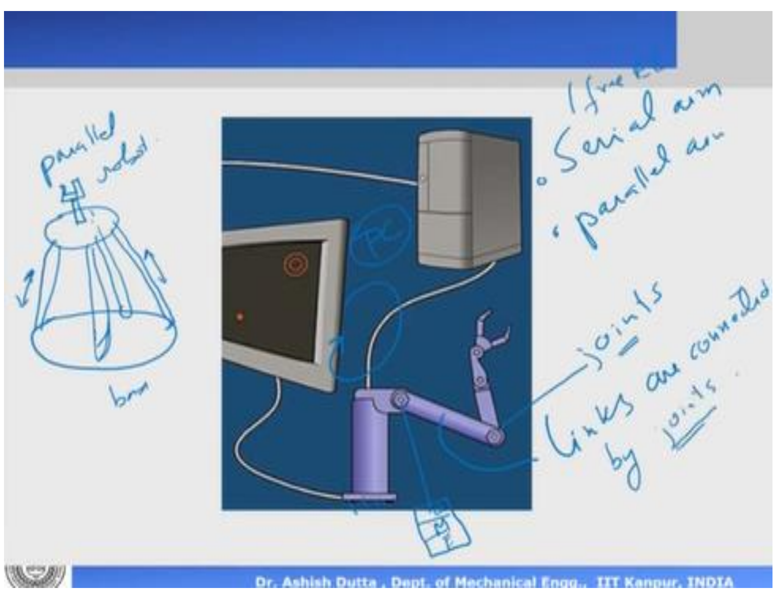

So, this is a mobile robot and this is a serial arm and this is a mobile robot, like a car, like a normal car I am sure you would have ridden on a car and you know how car moves. So, slowly, we will and look at planning path, planning for both of these applications. So, a robot basically consists of a link so, these are called links and these are called joints. Now this is a serial arm and you can have parallel alarms. Now in a serial arm the end is free as the name indicates.

Then a parallel alarm, it could be joined. For example, we have a robot like this there is one robot here. So, this is having a linkage structure like this. So, there is one link here, there is one link here and there is another link there. That is 1 link on that side that is it. Now this is let us say it can move up and down like this. These are prismatic joints but both ends are fixed. Now this is basically a parallel robot. So, this is a parallel robot where both the ends are fixed.

But it can still move. The top plate can still be positioned. So, I can put an end effector here. And it can still move. But both the ends you can see the base and the top is fixed. So, this is a parallel robot. In the case of a serial robot, the end effector is free. So, you can see that the end effector here is free. So, here it is a free end effector, end effector or gripper is free only one base is fixed. So, this is a serial arm like, you can look at, our arms.

It is fixed at the shoulder and our fingers we can move it in space it is not fixed anywhere. So, these are joints and these are links and the robot is controlled by a controller which can say it is a PC or it is a microcontroller. So, this is what basically makes up the closed loop control system. So, each of these joints will be driven by a motor. There would be an encoder at the back and there will be a gear in front and this is basically called independent joint control.

So, most of the serial arms are operated based on independent joint control. And they are operated by a controller which basically goes into the closed loop control system-based control. So, we have to look at the different kind of joints we can look at links. Then we look at how this moves around in space. The first thing that we; have seen that the links are connected by joints. So, links are connected by joints.

So, there can be different kind of joints which are imparting motion and the joints move, which imparts motion to the links. So, there can be different kind of joints.

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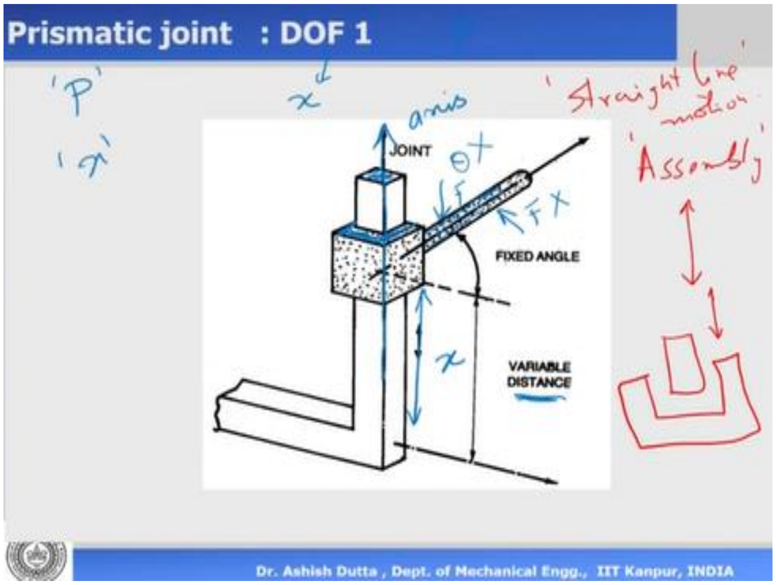

The first kind of joint is called a prismatic joint and it has degree of freedom 1. What is the degree of freedom here? It is the independent variable. So, when it moves what changes? So, as is shown here, we have a rectangular part. So, this is a rectangular part which is mounted onto another rectangular part which is here. Now as it indicates, this is called the axis. So, this is called my axis of motion.

Now, as is shown here this rectangular part suppose I have it here if I give it a force in that direction it cannot move. Why because it is a rectangle on another rectangle. Obviously, it cannot move there. It is very clear from here. So, it cannot rotate, it has no θ, it cannot rotate. But if I push it in this direction, then what will happen? It can move like this, up and down. And this joint is basically called a prismatic joint.

It can move in a straight line and the variable distance is x. So, that is my variable distance. And this is called the prismatic joint. It is also called translating joint and we can also denote this by P. If I say P joint it basically means prismatic joint. Degree of freedom is 1. What is the degree of freedom? It is x. It is a translating variable, so the variable distance. It has only one variable which can change it cannot rotate. So, it can only translate and that is 1 degree of freedom. And it is a prismatic joint.

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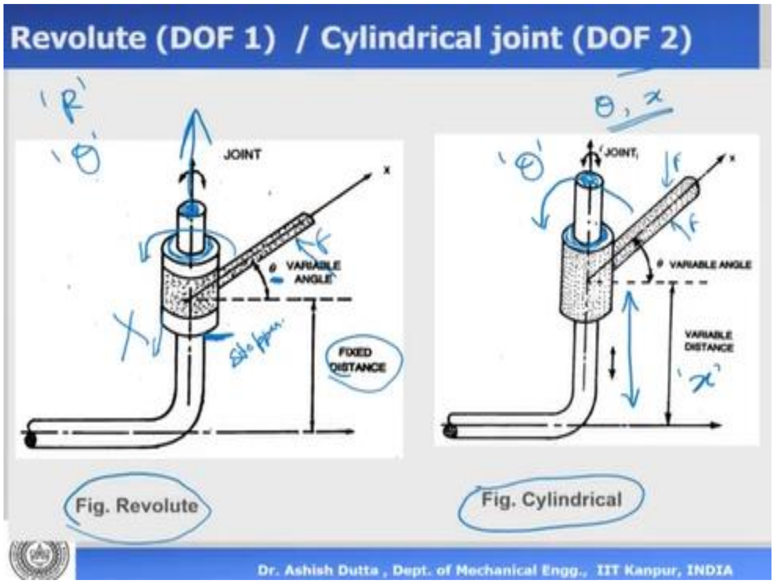

Next kind of joint is shown on the left side is the revolute joint. Now in this case, you have a cylinder which is mounted on another cylinder. You can see that. Now there is a stopper here. The stopper is required otherwise this cylinder can come down. So, it cannot come down. That is why the stopper is there. Now in this case where is the axis? This is the axis. Now if I give a force in this direction what will happen is because it is a cylinder on another cylinder it will rotate.

So, it will rotate like that and what is the variable that is changing? It is θ. So, here this revolute joint has 1 degree of freedom. This is called an R joint. And what is the variable? It is θ, and it is called an R joint. Now the stopper is placed so that this distance is fixed so it cannot move up and down. So, you can see that this is a revolute joint which has 1 degree of freedom θ is the degree of freedom.

In the previous case x is the degree of freedom, translating degree of freedom. Now on the right side, we have a cylindrical joint. Now in this cylindrical joint there is no stopper. So, the stopper that was there I remove the stopper there. So, it is a cylinder on another cylinder. But the stopper has been removed now. So, it can also slide like this and it can also rotate. So, if I give a force in this direction it will rotate.

If I give a force in that direction, it will go down or come up whichever way. Now in this case, there are two variables one is the θ which can change and the distance x which can change. So, this has two variables now which can change and hence it has 2 degrees of freedom. So, this has 2 degrees of freedom, θ and x, both are variables. And it has 2 degrees of freedom. Let us call it cylindrical joint.

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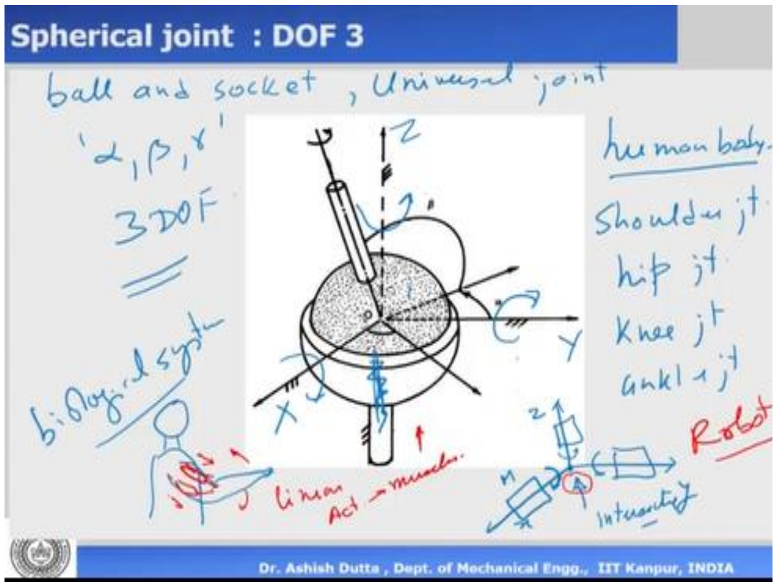

Now let us look at the third type of joint or the fourth type of joint which is called the spherical joint. Now, the spherical joint is also called a ball and socket joint you might hear this ball and socket joint. So, because there is a ball here so, this is a ball which is inside a socket so, that is my socket and, we assign axis. Let us say this is one axis X Y and Z so this is X Y and Z axis. Now, because it is a ball inside another spherical cavity. It can rotate about this axis.

It can rotate about that axis; it can rotate about this axis. It is a ball inside another ball I am sure you can visualize this. So, this can rotate in any direction actually. So, all and socket joint universal joint, they all mean the same thing. So, what are the variables? It is α, β and γ. How many degrees of freedom? 3 DOF. Now, in the human body, our shoulder joint is a ball and socket joint our hip joint is a ball and socket joint our knee joint, knee ankle.

These are all ball and socket joints. They give you maximum degrees of freedom because you can rotate in three directions. That is why in the shoulder joint we can move our arm in any direction. We can rotate in any direction because it is a ball and socket joint. Now, it is interesting to note that if you are making a robot which joint would you like to use suppose you are designing a robot. Now it would appear that we would like to use a ball and socket joint.

Why? Because it has 3 degrees of freedom you get maximum motion. But if you look at industrial robots serial arms about 99% of robots are made with revolute joints and this joint. So, this robot that I showed is also revolute joint. So, these are all R joints. They have one axis of rotation. This is my axis of rotation. Now, why is it that biological systems are made like this? So, but so, biological systems have ball and socket joints.

But robotic systems have revolute joints. What do you think? What is the problem? Now, you might say that manufacturing this is difficult. No manufacturing is not difficult can be made very easily these days. So, you can make it in two parts, for example, you cut it from here make it like two cups and then assemble it. And, then do laser welding or you can manufacture it separately. And then you can force fit this top fellow inside there or you can do rapid prototyping these days.

So, manufacturing is not difficult. And we have what are called roll bearings which are actually ball and socket type bearings or spherical bearings. So, making is not a problem. So, what is the problem? The problem is the control. Now, if you think a little bit, I have three axes. There is one axis like this, one axis like this, one axis like this, my x y and z axis. Now, how am I going to actuate this joint? I will put a motor, so there is one motor here.

There is one motor here and there is one motor there. These are motors. Now, this motor rotates like this this motor rotates like this, this motor rotates like that. Now, all three motors are meeting at that point in the centre there. Now, if you think a little bit if this motor rotates like this what will happen? It will tend to rotate the other motor also because they are all meeting at that point. So, what will happen?

One will start interacting with the other one and hence the control of this is not possible. So, we can make it but controlling these using motors is exceptionally difficult. Because you see that the motors are all intersecting there and that is what causes the problem. Whereas in biological systems you can argue that then how it is that it is used in biology? Now, biological systems do not use motors. What do we use? We use linear actuators.

So, if I draw a biological actuation so this is my biological actuation hand, your arm is like this. So, how is your joint moving? So, we have muscles here like this and like this. So, these muscles are connected to your elbow joint. So, how does this move? When this contracts the arm moves up when this contracts the arm moves down. And this is a linear actuator so when one is contracting the other one is relaxing.

So, they do not interact with one another unlike a motor here. So, in a biological system which are linear actuators which are basically muscles there is no problem in controlling this. And hence in our shoulder joint, hip joint, knee joint we have maximum motion. And they are actuated by linear actuators which is very different from the case of a robot. A robot is actuated by motors which are not linear actuators they are rotating actuators.

So, please understand this. This is something to understand about how motion is produced in biological systems and also in robotic systems. So, in robotic systems 99% of the time we use revolute joints having 1 degree of freedom. Now, a straight degree of freedom may be required for assembly. So, in the case of assembly, we require a linear actuator which is moving in a linear direction. But biological systems do not use this kind of joints.

You will never find a biological entity which uses a prismatic joint. We all use revolute joint cylindrical or your universal joint. But if you are doing assembly, for example, I want to insert this into this hole. Then, I may need straight line motion. And for straight line motion, this joint is required. For straight, this particular is required. And hence robots which do assembly one of the joints are normally a prismatic joint.

So, this basically gives us an idea of the various kind of joints and the degrees of freedom that are there.

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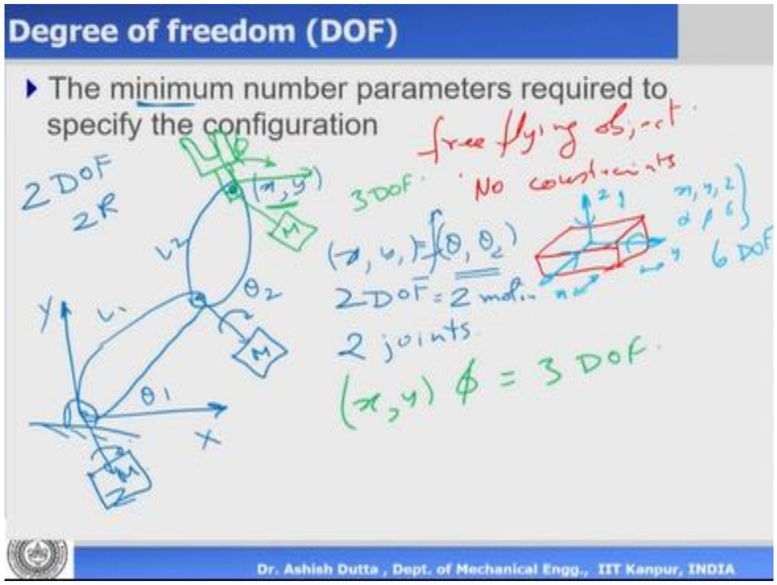

So, what is the degree of freedom? It is the minimum number of parameters required to specify the configuration of a system. So, let us take a free flying object, we are talking about a free flying object. What is the meaning of free flying object? It is not constrained with no constraints. So, if you are having an object like this. Let us say there is a cube or a cuboid which is freely floating in space.

Then, how many parameters are required to specify the configuration of the system? First let us say I put axis there. In the cg I am putting an axis x y and z, on the CG x y and z. So, it can have motion along the x direction, y direction, z direction. It can move like this it is free there no constraints it can rotate about x y or z so we can have an α, β, γ. So, how many are there? 6. So, these are 6 degrees of freedom.

So, freely flying object which has no constraints has 6 degrees of freedom to define the configuration. But the moment you start putting constraints now what are constraints? Constraints can be these joints the moment I fix 1 part the base of the robot and then we put joints. The joints are going to restrict your linkages now. And then all of them are going to determine what is the motion of your end effector?

So, the moment we start putting constraints what will happen? The degrees of freedom will come down. So, let us look at a robot like this. So, we have one link here and another link there and this is my end effector. So, this point is my x y it is in 2D. So, this is my x and that is my y. Now, so about the z axis this is my z. it can rotate like this. About this z also it can rotate like that. That is my z. So, there is a θ_1 there, there is a θ_2 there.

Now with θ_1 and θ_2 if this is my L_1, L_2, I can find what is x y. This is in 2D. So this coordinate here is having coordinates x and y. So, there is only x and there is only y. And there are 2 θ's, θ_1 and θ_2. So, how many degrees of freedom are there? Now this is planar to specify that x and y we only need 2 degrees of freedom, θ_1 and θ_2. So, the minimum number. Please note if I put 1 more degree of freedom the number of joints are going up.

But that x y still remains x y. So, in this particular case, you have a 2 degree of freedom system. This is 2 DOF. Now, you can see that there are also 2 motors. There is one motor here. There is one motor here. So, this one is 2 motors. So, it also has two joints. So, I am trying to show you the relation. So, for in the case of a robot we normally say the number of joints is the number of degrees of freedom provided each joint is 1 degree of freedom and they are not coupled.

So, in this particular case, the x y is a function of θ_1 and θ_2 and this has 2 degrees of freedom. Why 2 degrees of freedom? There are 2 joints, 2 revolute joints. And so, we write it as 2 DOF, degrees of freedom and there are 2 revolute joints 2. Now suppose I add 1 more linkage here. Let me add one more, I add an end effector. Now, x y still remains x y. But now this fellow will have an angle now. Let us say that has an angle Φ.

So, now, you have ended up by adding 1 more motor there. So, there is 1 more motor here. Now, so this becomes 3 degrees of freedom. So, you can control x y and the end effector angle Φ x y the position and that Φ is that angle of the end effector. So, this is basically what we mean by let us say this is my angle Φ, sorry the angle Φ is let us say with respect to x y this is my angle Φ. So, this is my x direction.

So, now we are saying that we have x y and we have a Φ which is the orientation of the end effector and hence this has now 3 degrees of freedom. How many joints are there? There are three joints, the 3 motors, 1, 2, 3. So, now you can see that for the robot we can count the number of joints and if they are 1 degree of freedom joints then the total number of joints is the degrees of freedom of the robot.

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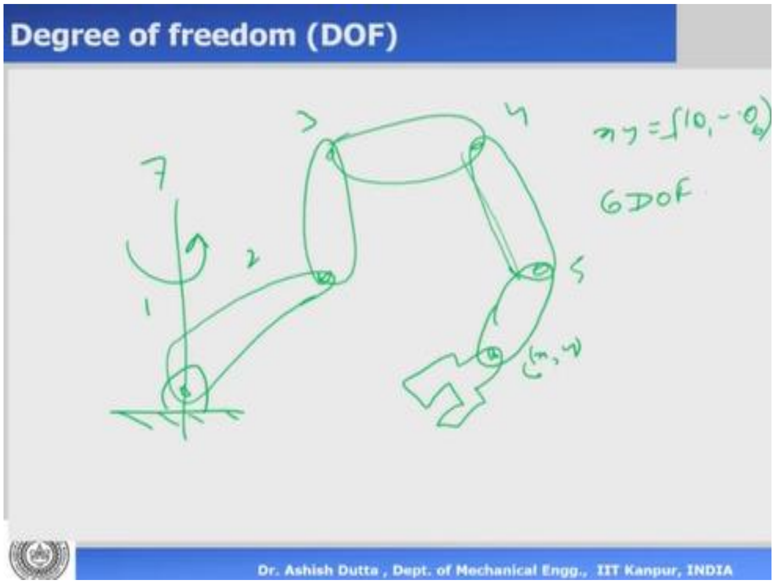

Now, what about in the case of a mobile robot? Now I can also add more number of degrees of freedom. Let us say, my first one is here 2, 3, 4 add one more here. Then I put an end effector. So, this has how many joints? 1, 2, 3, 4, 5, 6 it has now. That means this point x y, it is planar. So, it is x y is a function of θ_1 to θ_6. Now, how many degrees of freedom are there? 6 degrees of freedom over there. But it is still planar.

Now suppose I add one more joint like this and say this can rotate like this then I can add one more 7. So, this is basically in the case of a robotic system. We say the number of joints is the degrees of freedom of the system. This is just to differentiate between a free flying object here. We say this has 6 degrees of freedom what it means is that it can move in 6 directions. It has 3 translations 3 rotations whereas in the case of a robot.

We are saying that the number of joints that are there is the degrees of freedom of the system provided each joint is 1 degree of freedom. So, please distinguish between both of this. Now I hope it is clear what do you mean by a degree of freedom? And degree of freedom comes from the degree of freedom of the joint and how many joints are there. In the case of free flying object, it is the motions it has.

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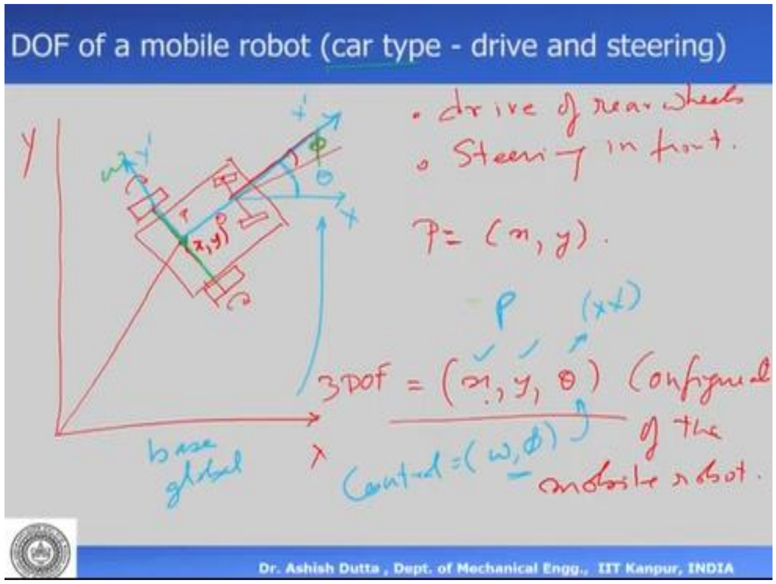

Now, let us look at a mobile robot. Now, this is a mobile robot. What is the degrees of freedom of a mobile robot? So, this mobile robot is a car type of robot so, it has a drive and it has a steering. So, the rear wheels can have a velocity ω and they are joined like this. And the centre point has coordinates x y let us call it the point P so the centre point is my point P and it has coordinates x and y.

So, to define the position of this robot you can define the position of x y and you know where is that point P. Now, it also has a steering now the steering is having an angle Φ. Now, we need to define what is the position of this car. And what is the orientation of the car. So, what we do is we fix another frame I fix a frame onto the robot base now. This is a frame I am fixing like this x and y now like this. So, this is my x and y for the robot.

And, then what I do is I take the angle, this angle and I call it θ. So, this is my x, this x axis, and this angle is making an angle of Φ. So, let us call this x'. So, the angle x and x' which is θ. That is giving me the orientation of the car with respect to the base frame which is my x and y so this is my base frame, base frame or global frame. So, now, how many parameters are required to define the configuration?

You need x and y which is giving the position P and you need θ which is giving the angle between x and x'. So, if I give you x y and θ you know exactly what is the position of the car. Now, how many parameters are the control variables here? How are you controlling this car? You are controlling the car parameters by giving an angular velocity ω to the wheel and the steering angle Φ.

Now, this is an interesting problem because your control variables are only 2, ω and Φ. But your output variables are 3 there. So, using this ω and Φ we are controlling x y and θ. So, this is an interesting problem which will come to when we talk about the systems having kinematic constraints. So, this is a mobile robot. Now there can be other kinds of mobile robots.

For example, in this particular case, we saw that the rear wheel velocities are the same and it has a steering.

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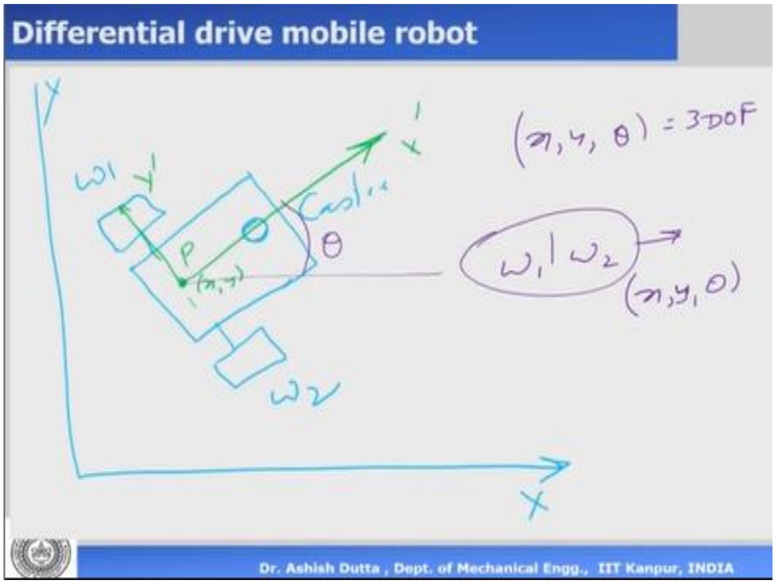

Now, you can also have a mobile robot which is like this where the 2 wheel velocities are different. So, these have 2 wheel velocities which are different. This is ω_1 and this is ω_2 and we have a caster wheel here. But here also it is exactly the same. So, this is my x and y global and we define I can take this point p and define the direction x' and y' which is local.

And then I can say that this coordinate is x and y this point P which is connecting the centre point between the two wheels. And I am going to define this one as my angle which is θ. So, here also, we have x y and θ. So, 3 degree of freedom and this is called a differential drive robot where there are 2 different drive wheels. So, how do you control this kind of robot? You have to control ω_1 and ω_2 and the output is x y and θ.

So, this is called a differential drive robot and we will look at this again as we come towards the end. And we start looking at systems with kinematic constraints. So, this basically today's discussion, we were able to understand what is a robot? Where did the robot come from? Then, we looked at the different kind of joints which are there. So, we looked at the definition of a robot today. Then, we looked at the definition of joints.

We saw prismatic, cylindrical and revolute joints and also universal joints. Then, we said about the degree of freedom of robotic system. That is how many joints are there we say the robot has that many degrees of freedom. And we looked at 2 kinds of mobile robots where we have one with differential drive and the other is the car like kind of robot. So, in the next class, we look at robots work volume that is the serial arm which has different degrees of freedom.

When we actuate the degrees of freedom the end effector moves in space. So, what is the geometry of the space in which the end effector moves? So, that is something that we will be seeing in the next class. So, let us stop today. Thank you.