INTELLIGENT CONTROL OF ROBOTIC SYSTEMS

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Lecture 01 Robotics: Primer-Robot Anatomy and Terminology

Good morning everyone. Today we are going to have the first lecture of my course on entitled 'Intelligent Control of Robotic Systems.' The first course is named 'Robotics Primer,' where we are going to see Robot anatomy and terminologies. The outline of this lecture will be as follows.

First, we have the robot anatomy, which includes joints and links, and then the terminologies, which will entirely focus on the work volume and the degrees of freedom. Then, we have the main components of robotic systems, which are actuators and sensors. In actuators, we are precisely going to see electric actuators and smart actuators. Then, in the sensors, we will be confined to optical encoders and force sensors. Coming to the robot anatomy, the robotic system is composed of joints, links, actuators, and sensors. So, there are various robotic systems: a humanoid robotic system, an exoskeleton meant for the movement of the limbs of human beings, and medical robotic systems, which will be helpful for minimally invasive surgeries. First, let us take

the humanoid robot, where we have the links as rigid and the actuators mainly as electric actuators. We can see that the exoskeleton meant for rehabilitation purposes also has the links and the actuators. The links in the case of humanoid robots are basically straight links, straight rigid links, or serial links. You can see Whereas, in the case of the exoskeleton, in this schematic, you can see it is basically composed of links and is basically a series of mechanisms. Here, we have four-bar mechanisms connected in series. And the joints here, in the case of the medical robotic system, represent a prismatic joint. And thus, robotic systems

Include several joints and different types of links. Different types of links, I mean rigid links as well as flexible links. Now, coming to the types of joints of a robotic system. The first and simplest joint is the revolute joint, which has one degree of freedom. What is the degree of freedom?

We are going to see it in the upcoming slides. So, the revolute joint has one degree of freedom where the joint variable is represented by theta and d. Q is the joint variable, theta is the joint variable for the revolute joint, and d is the joint variable for the prismatic joint. As I mentioned earlier, the revolute joint has one degree of freedom where the variable is the rotational joint angle. It is mentioned here as theta.

In the case of the cylindrical joint, we have a combination of the prismatic joint, where the joint variable is the distance d from the origin or from the initial portion, and the second joint variable is theta, which is the joint angle or rotational angle. So, combinedly, we have the cylindrical joint, and hence the degree of freedom is 2 for the cylindrical joint. Because it has a prismatic and revolute joint combined. In the case of the spherical joint, we have three degrees of freedom, which indicate roll, pitch, and yaw. Okay, when we take a coordinate frame, say x, y, and z, where x is pointing outside, we can say that

The orientation around the x-axis can be roll. The orientation around the y-axis can be pitch. The orientation around the z-axis can be yaw. And hence, this joint represents three degrees of freedom. Now, coming to the end effector.

What is an end effector? It is a special tool for a robotic system that enables it to perform a specific task. That means it is a device attached to the robot's wrist in order to perform a specific task. There are two types of end effectors.

One is called a gripper in order to perform grasping and manipulating objects tasks during the work cycle, and another type of end effector is called a tool gripper. In order to perform a process called spray painting or spot welding, now coming to the terminologies associated with the robotic systems, one is work volume, and work volume indicates the volume inside which the robot can perform or position its gripper. That means the given task to be performed by a robotic system must be given well within the work volume. For example, when we consider a 2-degree-of-freedom robotic system where this is L1, this is L2. We have two joints here.

Joint 1, say theta 1. Joint 2, say theta 2. And let us say that theta 1 varies from 0 degrees to 90 degrees and theta 1 varies from 0 degrees to 180 degrees. Again, I repeat: theta 1 varies from 0 degrees to 90 degrees, and theta 2 varies from 0 degrees to 180 degrees.

So, when we have this, we can say that theta 1 is 0, and you move theta 2 from 0 degrees to 90 degrees, so you will have this. We have theta 1 at 90 degrees, so it becomes the robotic system. This system becomes this, and we have the variation of theta 2 moving from 0 to 90 degrees. So, what is observed here is right. What is observed here is that we have this region as a work volume, and we have obtained this region as the work volume line. Then, you keep this, for example, you keep here 90 degrees for theta 1 and theta 2 is also 90 degrees. Then, keep theta 2 at 0 degrees and move. You have this one coming into the work volume. Because of the 0 to 90-degree variation of theta 1, and you have this theta 2 varying from 0 to 180 degrees, you have this portion combined also. Hence, this is the complete work volume of a 2 degrees of freedom. This is the work volume for a 2R planar robot.

That means the work volume of a 2 revolute jointed planar robot. Let us say if it is a 3 revolute jointed planar robot, which means this, this, and this. L1, L2, L3. So theta 1, theta 2, theta 3. So, how can we get this type of work volume? That is again obtained by varying theta 1 from 0 to 90, theta 2, and theta 3 varying from 0 to 180 degrees.

You will be getting this. And this is the plot obtained from MATLAB, where we have the outer loop for theta 1 and the nested inner loops for theta 2 and theta 3, respectively. All three vary from 0 to 90 and and 0 to 180, respectively. Now, let us see the work volume for standard robotic systems used in the industry.

First, let us take a Cartesian robot. The moment I say Cartesian robot, it indicates that the joints of the robotic system are made up of prismatic joints, which means the variation of the joint is d, q equal to d, d for distance. That is why, when we see the side view of the work volume of this Cartesian robot, we can see a square area. Similarly, the top view is again a square area. It is all because of the Cartesian joints it has.

Q1 equal to D1, Q2 equal to D2. We can see here that the functioning of this Cartesian robotic system is where all its joints are prismatic. You can see that they move in a straight line, not in a rotary movement.

Okay. This is the real functioning of a robotic system. Taken from ADAPT. Work volume. Work space.

Or website, you can say. And now, let us move on to. Now, for the cylindrical robot. Which is a combination of both. Prismatic and revolving joint.

We have the work volume seen from the side view. Is going to be the. Square area, whereas the top view is a circular area, and the real functioning of the robotic system is shown here, which is a combination of revolute and prismatic joint for pick-and-place application. Next, we can Represent the configuration of a robotic system in terms of its independent coordinates Q. Whereas, for the Cartesian robot, it is a combination of prismatic joints alone, and hence the 3 degrees of freedom Cartesian robot is configured as P, P, and P. That means it has 3 degrees of freedom Continuously with prismatic joints.

Similarly, for a cylindrical joint, you can say that the first joint is a revolute joint, with joint variable theta. The second joint is a prismatic joint, which is D1, say D2, theta 1, D2, and the third joint is D3. And hence, the configuration of the cylindrical joint or cylindrical robotic system is R, P, and P. Similarly, for a spherical joint, we can say it has 3 degrees of freedom. For this robotic system shown here, we can see theta 1, theta 2, and d 3.

That is why it is R, R, and d, which is P, prismatic. Similarly, for an articulated robotic system, what do you mean by articulated robotic system? It means every joint there is meant for rotary motion. It has all the joints of its system being revolute joints. And hence, how many degrees of freedom?

R, R, and R, which means 3 degrees of freedom, constituting all the rotary movements. Next, for the SCARA robot, which is Selective Compliance Assembly Robotic Arm, it has 4 degrees of freedom. I add the fourth degree of freedom. Okay, so that is R, where the gripper is going to be oriented by an angle theta 4, and hence we have theta 1, theta 2, d 3, and theta 4. That's why the SCARA robot has four degrees of freedom, with one prismatic joint for the third joint and the rest all being revolute joints. Now, coming to the actuators, which play a vital role. In order to move a robotic system.

Here, we are confined to two types of actuators. One is electric actuators or electric motors, and smart actuators. So, coming to the electric actuator, which is a fundamental actuator used in robotic systems, is a DC motor where the principle of working is given in such a way that when a current-carrying conductor is placed in a magnetic field in such a way that the direction of current passing through the conductor is perpendicular to the direction of the magnetic field. And in that situation, a turning force is generated, which is perpendicular to both the magnetic field direction and the current direction.

And this law is given by Fleming's left-hand rule. That means when the middle finger points in the direction of current and the index finger points in the direction of the magnetic field, then the direction of the thumb gives the direction of the turning force. And the control of a simple DC motor is given in this video here, where speed is taken into account. First, we can say given rpm, say 100 rpm, then 50 rpm, then 30 rpm, then suddenly 80 rpm, then 150 rpm.

So, the speed is the desired quantity in order to have the speed of the robotic motor controlled. To the desired speed, the motor should rotate. Here, the components of the electronic circuitry are the power supply, the DC motor, and the driving circuitry, which is in order to have the power amplification because the motor draws more current. So, we need to amplify the power. That is why a power amplifier is used.

It is the L293 power amplifier, which is an H-bridge circuitry, and we have an interface, which is basically an Arduino UNO board. Sometimes, National Instruments' data acquisition card can be used as an interface between the software and the motor hardware. Now, coming to the stepper motor, which basically has two parts, as in the case of a DC motor. We have a stator and a rotor. The rotor, as the name indicates, is going to rotate.

It is the central part, and the stator is fixed in the outer part. And when the stator sits, see, this is the first combination, and this one is the second combination. When the first combination is excited, the rotor aligns itself to the excited stator windings. When the second stator winding is excited, and keeping the stator winding set one off, we can see that the rotor is turning 90 degrees from the initial case, so that it is now aligning to the excited stator set 2 windings. When all the stator windings are excited, that means stator set 1 and stator set 2 both are excited at the same time, then we can have the rotor aligned exactly in between the stator coils, and hence earlier it was 0 to 90 degrees, and now it is 45 degrees.

That means it aligns itself exactly between the stator windings, and roughly 1.8 degrees is the minimum step angle of the general stepper motor. In order to increase the step angle, what can we do? We need to increase the number of stator windings, which means that I need to have the accuracy better than 1.8 degrees, which means that the I need to have precise movement of the motor shaft. In the case of a stepper motor, I need to have more stator windings so that once the adjacent stator windings are excited, we can have the shaft to be lying in between the stator windings, so that the angle value can be more precise and smaller in order to achieve that small desired angle value.

And here is the circuitry. For the stepper motor, and when we connect this, as I mentioned earlier, power amplifier circuitry, interface circuitry, and this motor with the external power supply to the motor driver, we can have the application of the stepper motor shown here, where the system has a part where we can have a medical needling system to be moved up and down. By the stepper motor functioning, we can have the platform coming down and moving up as per the clockwise and anticlockwise rotation of the stepper motor. Next, we can have the DC servo motor, which is very cheaply available as compared to the cost of a DC stepper motor and a DC brushless motor. These are the components that are inside the assembly of a DC servo motor.

We have an inbuilt potentiometer so that whatever angle we expect to move, the shaft of the DC servo motor will move to that angle exactly. That exact moment is given by the internal potentiometer, which gives the feedback value. And we have a gear train also in order to have high torque for this motor, the DC servo motor. And here is an application where we use the same DC servo motor in order to have the spinning of this needling system to enter a tissue volume. Exactly, the spinning is done by this

This DC servo motor. Next, we move on to the smart actuator, where we focus on the shape memory alloy actuator, which is the SMA actuator. There are two smart actuators, you can say: one is the shape memory alloy actuator, and another one is a piezoelectric actuator. Here, we confine ourselves to only the SMA actuator. It is available in two forms. One is the wire form. Another one is the spring form.

In two forms, this wire actuator called the SMA actuator is available. One is the wire actuator. The other one is the spring actuator. This has a salient feature where its power-to-weight ratio is high. Because its volume is very small, as you can see here, this is the wire actuator, the SMA wire actuator. It has a diameter of 0.45 millimeters, and we can say that the SMA actuator is basically a metallic ion, a metallic alloy which is a combination of nickel and titanium. It's also called Nitinol.

The wire actuator, Nitinol actuators, because it is a combination of two metals, two alloys you can say, nickel and titanium, so the phase transformation happens for this actuator in order to perform the actuation task. That means during the heating of this alloy or the nickel-titanium alloy, we can say that when it is heated, the actuator can be formed into any desired shape, either a wire shape or a spring shape. And then, upon cooling, it comes back to twinned martensite, which means that the austenite is the high-temperature phase structure of the SMA wire, and martensite is the cold-phase temperature structure, crystalline structure you can say. So, when it is heated, it goes to the austenite phase.

When it is cooled, it goes to martensite. In the cooling stage, it has twinned and deformed phases. That means when it is cooled, it comes to twinned martensite, and upon loading, it goes to deformed. Upon loading is the time where we do our application, and in the loaded condition, when it is heated, it goes to the original shape. By its memory, it goes to its original shape because it memorizes where it

And which was its original shape. For example, in this application here, we have a needling system which is actuated by this wire actuator attached to the lateral side of this needle. When we power it and pass current through this circuitry, we have Due to Joule's heating effect, $H = I^2R$, we have, due to the current flowing through this needling system, the contraction of the wire. This means that this is the deformed shape of the wire, and this is the austenite original shape. And upon heating, it returns to its original shape. That is why the length is getting contracted, and hence the needle bends.

And upon cooling, it goes back to its martensite phase. Another application is shown here, where we can see that it goes to it goes to Maneuvering in free space, this is the needling system we have developed in our laboratory. The actuator is attached to the lateral side or surface of this needle so that we can have this bending of the needle happening not by a DC motor, which is bulky, but by a smart actuator, which is an SMA wire actuator attached to the lateral surface. Now, coming to the final actuator part, which is the electrostatic micro actuator, which means that the actuators used in the micro robots. One of the most commonly used actuators is the electrostatic micro actuator.

So, the working principle is such that when we apply voltage to the two parallel plates or two parallel electrodes or to the capacitor plates, A force, so-called electrostatic force, is developed because of applying potential across these two parallel plates. Opposite charges are induced in the two parallel electrodes in such a way that the electric potential causes the forces to be induced, and the two plates try to come together. That means the force generated Is an attractive force. That is given by the expression $1/2 * \varepsilon * S * V^2 / D^2$, where ε is the dielectric medium between the two plates, S is the surface area of the electrode, V is the applied voltage, and D is the distance between these two parallel plates. One of the applications where we find this electrostatic micro actuator is in the micro robotic system, where this combination or this assembly is called the parallel plate comb micro actuator, used in the micro robotic system.

Next, we move on to sensors. We confine this lecture purely to the encoders. So, we are going to see two types of optical encoders here, which are attached to the motor shaft. The first one is the absolute optical encoder, where it has a disk with several tracks. Let the number of tracks be n, and each track will have different coded regions.

The coded region is represented by the black color here. And the transparent region is not coded as 1. Now, let us say that this has 4 tracks. The disk has 4 tracks. The outer ring or the outer track indicates, let us say, 2 to the power of 0.

And the second outer ring indicates 2 to the power of 1. So, collectively, we can get the decoded 1. value in order to get the sector indication. So, you can see the assembly of this absolute optical encoder to a motor shaft will collectively have this assembly, which means we have a disc on one side of the disc, we have a light source, and on the other side is a photo detector to receive the light source passing through this white-colored region, that means one region is opaque, and another region is transparent. So, once the shaft rotates, the disc attached to the shaft also rotates along with the shaft. So, once one of the sectors passes through this light source region, then accordingly, we will get the

Photodetectors are giving the values. Let the outer ring, as I mentioned, be indicated by the value, say coded value 2^0. Similarly, the second outer ring is 2^1, and depending on the relative position of the shaft, we get 1s and 0s coming out from the photodetectors' signal processing unit. So, the decoded value, let us say, is this case. The second shaft or second sector, you can see this is sector number one, this segment two, so the decoded value for this case is going to be $0 * 2^0$ because the 0 is indicating this opaque region and $1 * 2^1$ here is transparent, here is transparent, here is transparent. Another three inner tracks of that particular sector are

So, we get the light source passing, the light passing through this transparent region, and hence the detectors will give values 1, 1 accordingly. And hence, we can have that multiplied to get the final value coming to be 14 for that particular sector. Now, the angular resolution for this absolute optical encoder is given by the expression $360° / 2^n$, where n is the number of tracks. For example, if we have n equal to 13, the resolution is going to be 0.044°, and hence the angle is going to be computed as the resolution multiplied by the particular number of the sector, which is between 1 to 8192. Now, coming to the next type of optical encoder, the incremental optical encoder.

Here, this is the shape of the incremental optical encoder. It has n radial lines, and for this optical encoder, we have the resolution given by 360 / n, where n is the number of radial lines. So, the actual angle is the resolution multiplied by the counted pulses. So, when we have received the pulses from channel A and channel B, which means that two adjacent receivers.

One receiver gets pulses. Similarly, another receiver also gets pulses. Let the receiver one output be termed as channel A output, then the receiver 2's output is represented as channel B output. If channel A leads channel B's output, then we can say that it rotates in, say, a clockwise direction. Similarly, if channel A signal lags channel B, then we can say that it is rotating in the opposite direction or counterclockwise direction. Now, coming to the final part of this sensor, which is the force sensor. Generally, the force sensor is made up of a deformable part, which means that a portion of the sensor where the pressure is applied, that is, this is a region where the pressure is going to be applied, so that region we generally have strain gauges occupying the sensor. The principle of the strain gauge is given by the change in resistance, which happens by an expression, which is $R = \rho L/A$, where ρ is the resistivity, L is the length of the conductor, and A is the cross-sectional area of the conductor. So by varying any of these parameters ρ, L, and A, we can have the resistance of the strain gauge change, and during the resistance, due to the change in resistance, we can have the voltage of the Wheatstone bridge circuitry getting changed. Okay, so by the Wheatstone circuitry changed

in the null condition, we have the bridge balanced. The Wheatstone bridge is balanced, and in the Wheatstone bridge, we have only one variable resistance provided by the strain gauge. Once the strain gauge is not having any change in resistance, then we can say the bridge is balanced. Once we have This is coming out as a balance equation. Once we have, say, R1 as a strain gauge resistance changing, we have the bridge unbalanced, and accordingly, we have the output voltage V0 that is proportional to the change in resistance of the strain gauge. This value is proportional to the applied force. That is the principle of the force sensor in the robotic system.

The simplest force sensor available is the FSR 402. Its cost is around 200 rupees. This has been utilized in our laboratory for an exoskeleton grasping an object, where we have the force sensor in contact between the object and the fingertip to measure the force value. So, in this lecture, we have covered topics on robot anatomy involving joints, actuators, and sensors. Specifically, in sensors, we have seen encoders meant for positioning measurement and force sensors for measuring the interaction force between the environment and the robotic end effector.

The terminologies we have discussed here are degrees of freedom and work volume. It is required and suggested by me that you solve for the 3 degrees of freedom planar robot to determine the work volume using MATLAB M script. You can try this by implementing 3 loops in a for loop, with the outer loop for theta 1 varying from 0 to 90 degrees and the other two joint angles, theta 2 and theta 3, varying from 0 to 180 degrees. Thank you very much.