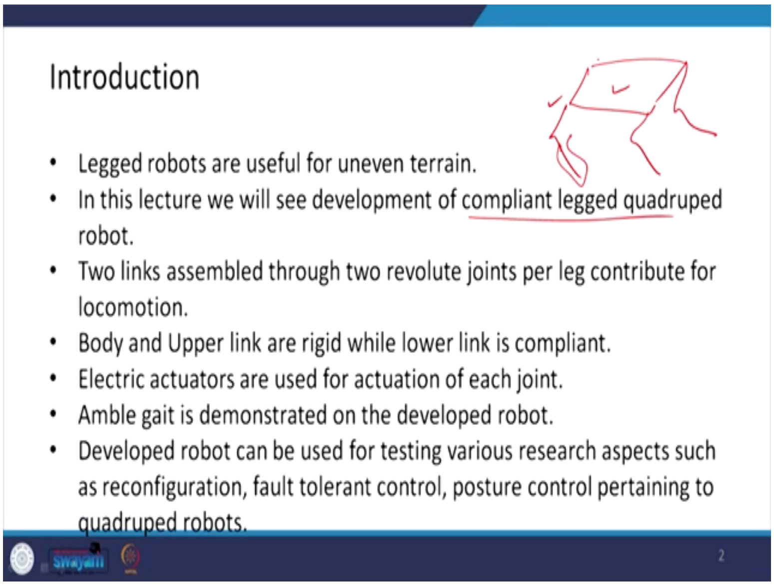
Mechatronics
Prof. Pushparaj Mani Pathak
Department of Mechanical and Industrial Engineering
Indian Institute of Technology, Roorkee

Lecture - 40
Design of a Legged Robot

I welcome you all to this lecture on the Design of a Legged Robot. We have been seeing many examples of the design of a Mechatronic system over the last few lectures. This is the last lecture in that series, where I will discuss with you the various steps involved in the design of a legged robot that was carried out in our lab. You know, legged robots are very useful for uneven terrain because these legs can be placed in a small area. So, they are suitable for uneven terrain.

(Refer Slide Time: 01:25)

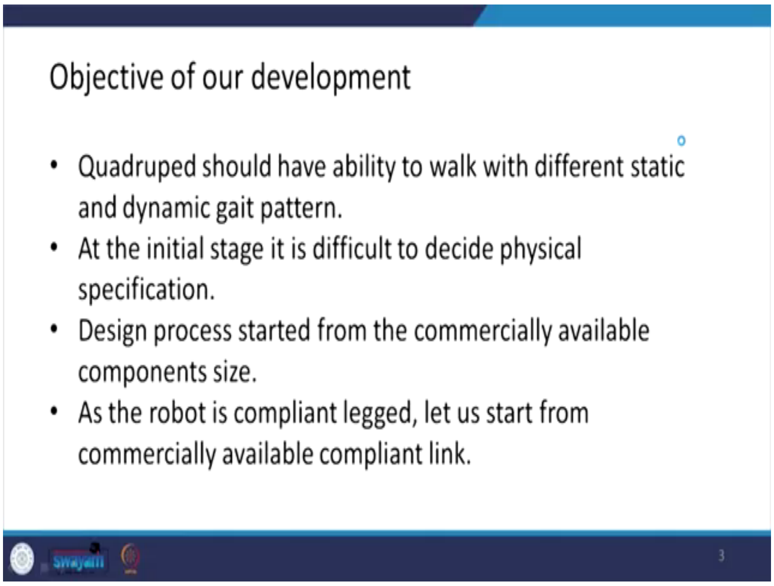


Here I am going to talk about the development of the compliant legged quadruped robot. The two links of the robot we are going to discuss today.

The bottom-most bottom link is the compliant one which we have considered over here, and the body and the upper link are rigid ones. And the electrical actuators are used for the actuation of each joint we have already seen a lot of detail about the actual electrical actuators. Here, an amble gait is demonstrated on the developed robot. An amble gait is one you see that they have got four legs. So, one leg is in contact with the one leg is in the air, whereas the three legs are in contact at the ground, which is what we call the amble gait.

This developed robot can be used for testing various research aspects such as reconfiguration for tolerant control posture control pertaining to the four-legged robots. The objective of our development has been the robot should be able to walk with different static and dynamic gait patterns, and I am taking this example over here after learning all the various mechatronic components of actuator sensors.

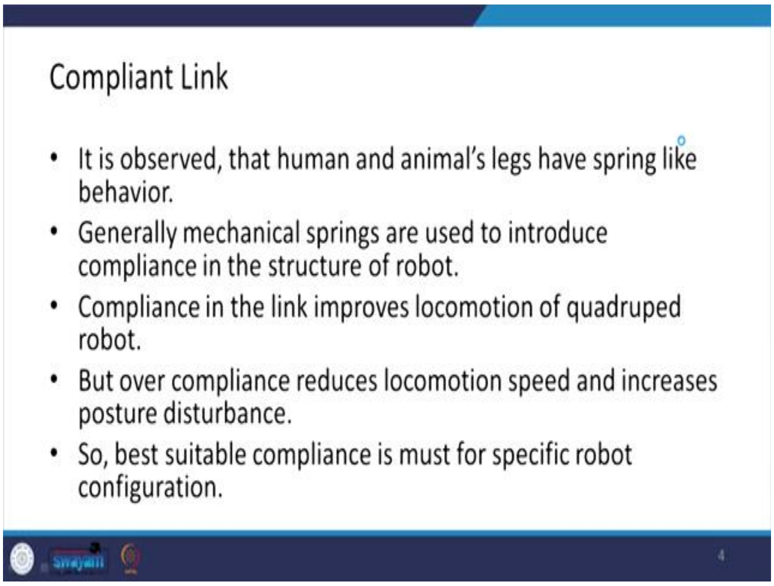
(Refer Slide Time: 03:13)



With microcontrollers, digital control, analog control, and all these aspects of any mechatronic system design has the ultimate aim of the development of a mechatronic product. This legged robot is a very good example of that mechatronic product.

At the initial stage, it is difficult to decide the physical specification, and as you know, the design of any component is an iterative process. So, you have to begin from somewhere. The design process started from the size of the commercially available components. As the robot is compliant legged, let us start from the commercially available compliant link.

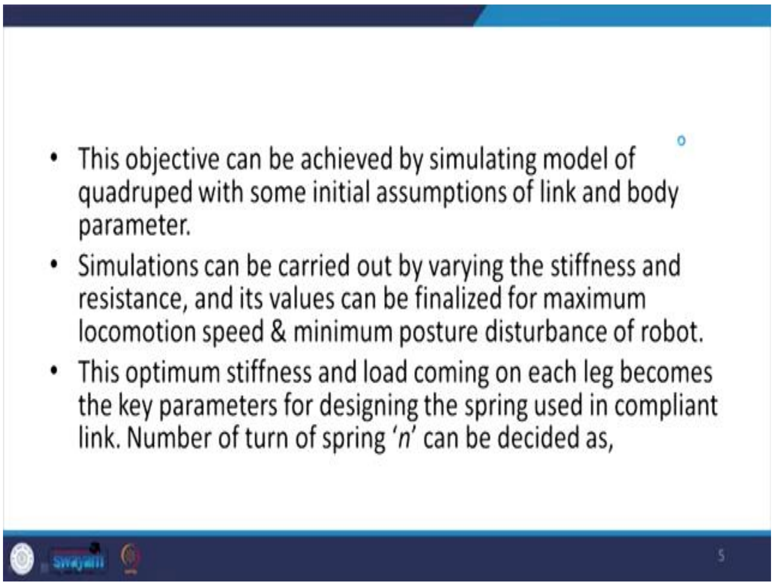
(Refer Slide Time: 04:15)



Now, the compliant link is observed. That is why we took the compliant link because it is observed that the human and animal legs have spring-like behavior. And generally, mechanical springs are introduced to introduce compliance in the structure of a robot.

Why do we go for compliance? Because compliance improves the locomotion of the quadruped robot. Of course, it increases a certain problem also that is it reduces the locomotion speed and increases the posture disturbance. So, the best suitable compliance is must for the specific type of robot configuration.

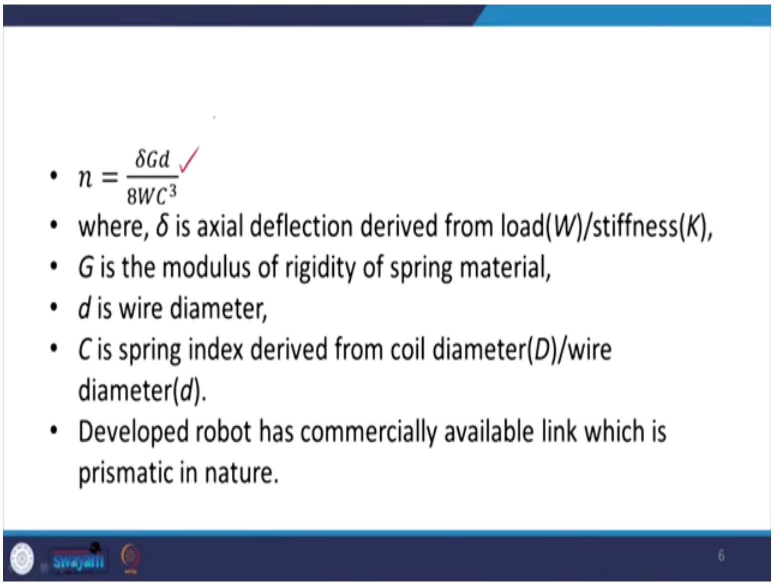
(Refer Slide Time: 05:02)



The objective can be achieved by simulating the model of a quadruped with some initial assumptions of link and body parameters. The simulation can be carried out by varying the stiffness and resistance, and its values can be finalized for maximum locomotion speed and minimum posture disturbance of the robot. Now, the optimum stiffness and load coming on each leg become the key parameter for the design of the spring used in the compliant link. Suppose the number of turns of the spring can be decided by the popular formula, that is,

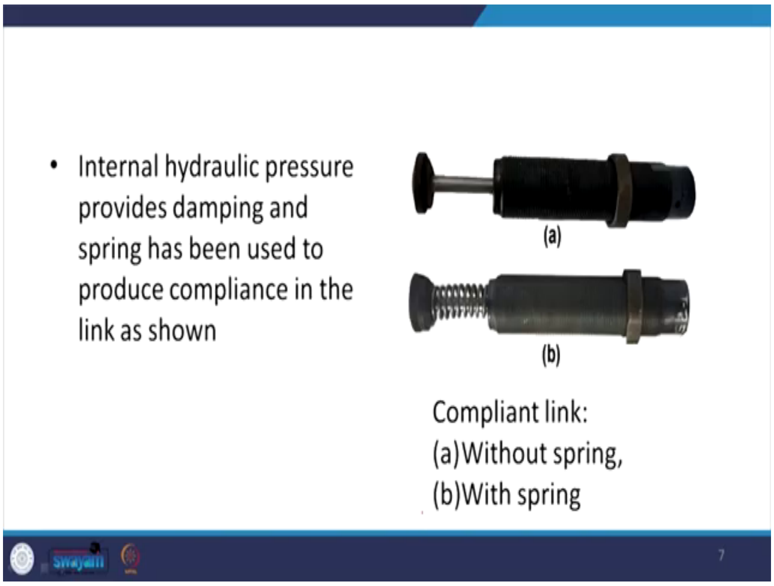
$$n = \frac{\delta G d}{8 W C^3}$$

(Refer Slide Time: 05:55)



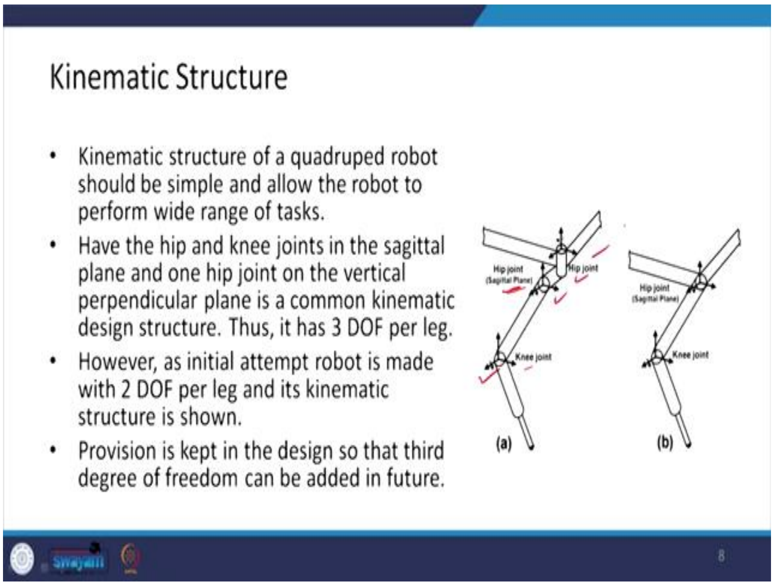
Where δ is the axial deflection derived from the load (W) versus stiffness (K), G is the modulus of rigidity of the spring material, d is the wire diameter, and C is the spring index derived from the coil diameter to the wire diameter (d). And developed robot has a commercially available link that is prismatic in nature.

(Refer Slide Time: 06:22)



This is what we procured. It is internal hydraulic pressure. There is an internal hydraulic pressure providing damping, and spring has been used to produce the compliance here. So, we inserted this one over here in order to introduce compliance in the link.

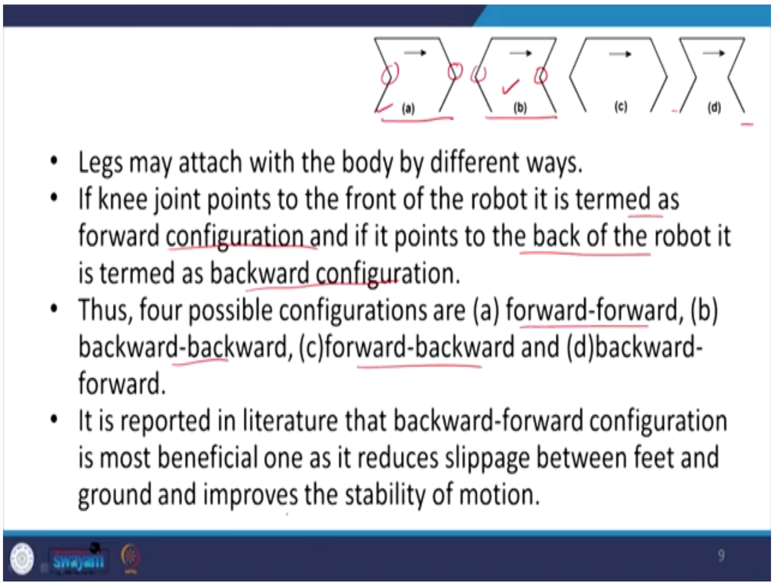
(Refer Slide Time: 06:42)



Then coming to the kinematic structure of the robot, we assumed the knee joint and the two hip joints. This hip joint and this knee joint are in the sagittal plane, whereas this hip joint is in the vertical plane.

Usually, the kinematic structure of a quadruped robot should be simple, and it allows the robot to perform a wide range of tasks. Here, you can see that we provided this hip joint feature for additional degrees of freedom, but this was the provision only in the developed robot that is not there. Next, how the leg should be positioned and how the leg should be attached to the body. There are different phases in which the leg may be attached to the body if they need knee points to the front, as you can see over here.

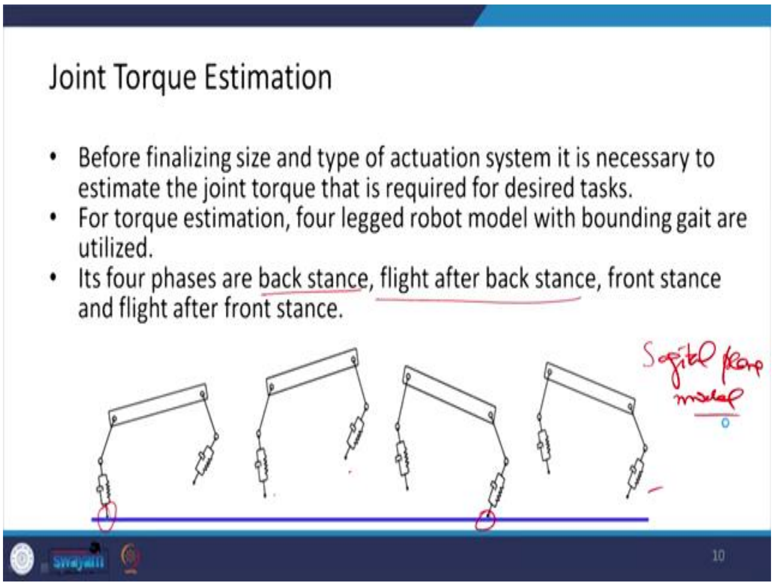
(Refer Slide Time: 08:05)



The robot is termed as the forward configuration, and if they point to the back, the robot is termed as the backward configuration. So, this is the backward configuration, and this is the forward configuration. We have the four possible configurations. These are the forward-forward. So, this is the forward-forward, or we have the backward-backward. And this one is forward-backward, and then we have the backward-forward.

Here, it is reported in the literature that the last configuration, which is the backward-forward configuration, is the most beneficial one as it reduces the slipping between slippage between the feet and the ground and it improves the stability of the motion.

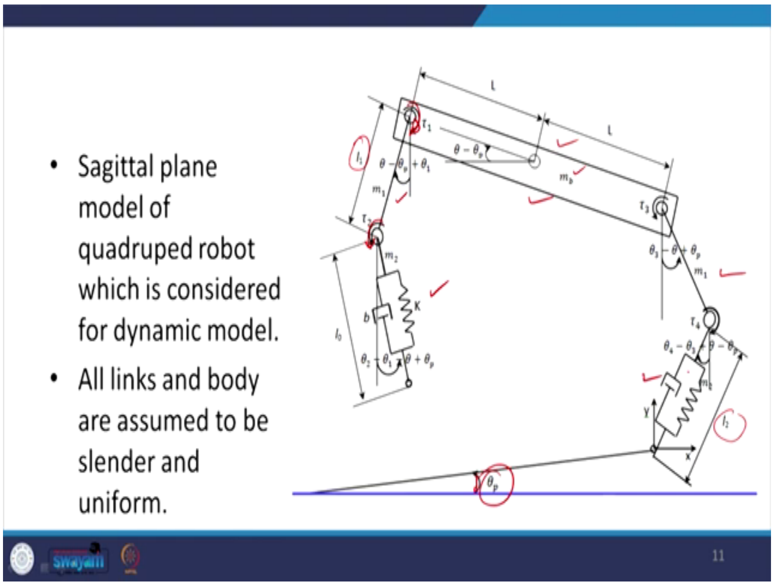
(Refer Slide Time: 08:55)



The next task was on the selection of the actuator. To select the actuator, we need to do the estimation of the torque what size of actuator we are going to take. For that, we do an estimation of the torque of the four-legged. Here, we model the bounding gait and the four phases. In the case of bounding gait, the four phases are this is the back in contact with the ground, so we call it the back instance. Here both the legs are there in the air, so this is the flight after back stance, and here this is the front stance. The leg is front leg is in contact with the ground, and this is the flight after the front stance. So, here again, both the legs are there in the air.

This is what I was telling you the sagittal plane model of the four-legged robot. As I said after deciding what configuration we are going to use, we, as I said, we selected here.

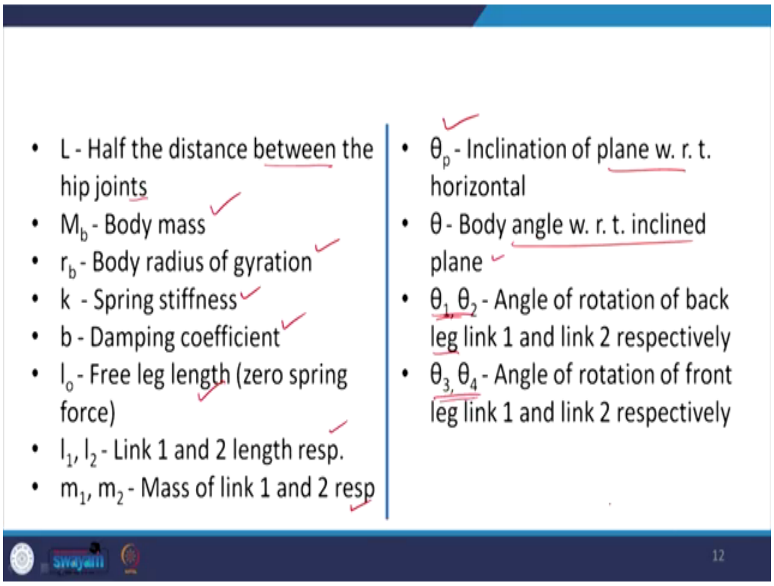
(Refer Slide Time: 10:41)



After deciding what configuration we are going to use, we can calculate this torque requirement. Here is the basic schematic for that we considered an inclined plane here with angle θ_p and this is you can that the sagittal plane model these are the bottom links which are complied and this one is the rigid link, this one is the rigid link, and this is the body, and other parameters are specified over here such as link length.

Here L_1 link length here and then what? The mass of both and here are the two joints for the rear leg, and here are the two joints for the front leg. So, all links and bodies are assumed to be cylinder and uniform, and that is why we considered this sagittal plane model because the derivation of the expressions is simpler.

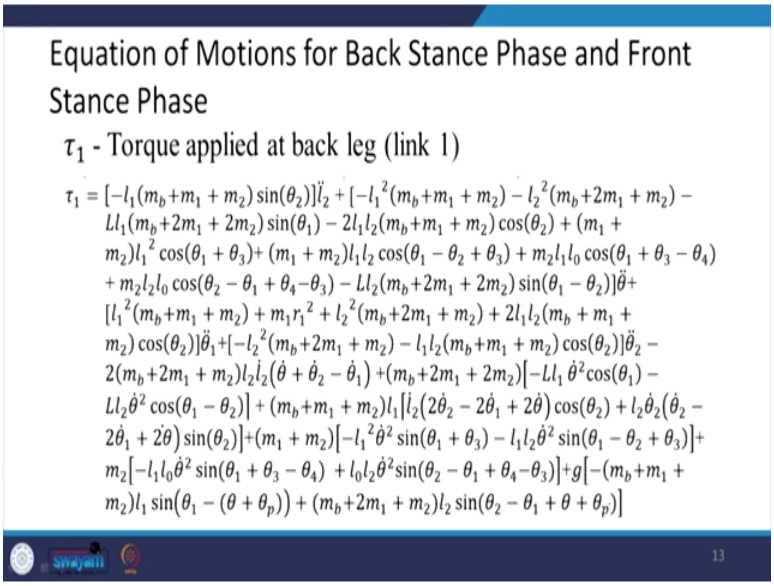
(Refer Slide Time: 12:03)



Here in this slide, all the parameters are defined. Half of the distance between the hip joints body of the mass body mass, body radius of gyration, spring stiffness, damping coefficient, free leg length zero spring force, L_1, L_2 link with lengths, respectively, m_1, m_2 are masses of links 1 and 2, respectively.

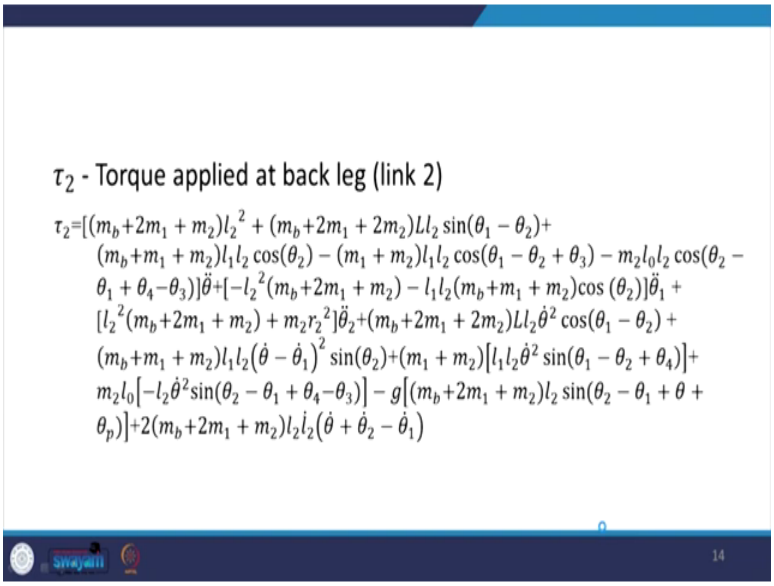
Then this is the inclination of the plane, this is the body angle with respect to the inclined plane, and these are the joint angles of the back leg θ_1, θ_2, and θ_3, θ_4 are the that of the front leg.

(Refer Slide Time: 12:47)



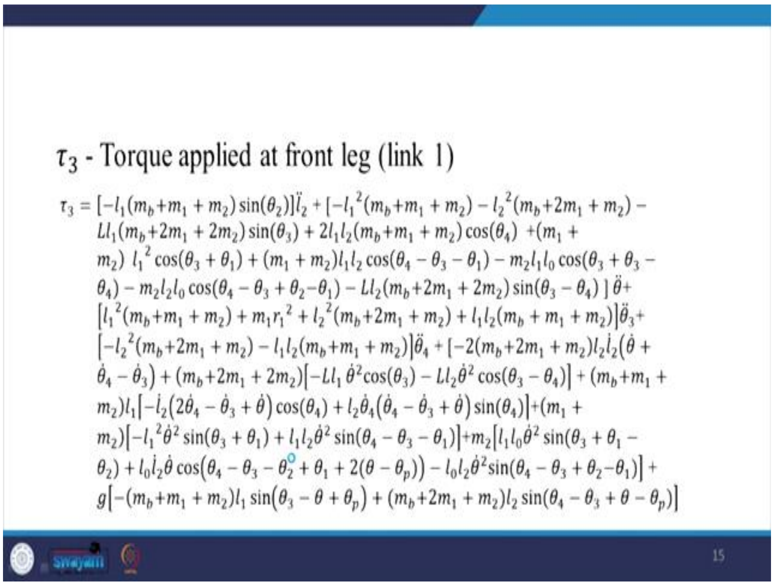
So, the equation of motion for the back stance phase and the front stance phase is here. The torque applied at the back leg is in the case of link 1. You can see there is a huge expression over here involving all the parameters.

(Refer Slide Time: 13:18)



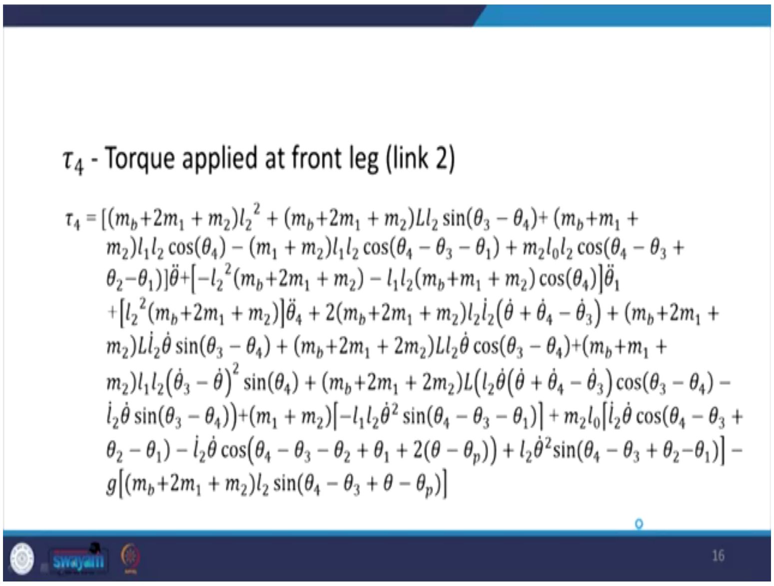
And the torque applied at the back leg that is the link 2 can be evaluated over here like this.

(Refer Slide Time: 13:32)



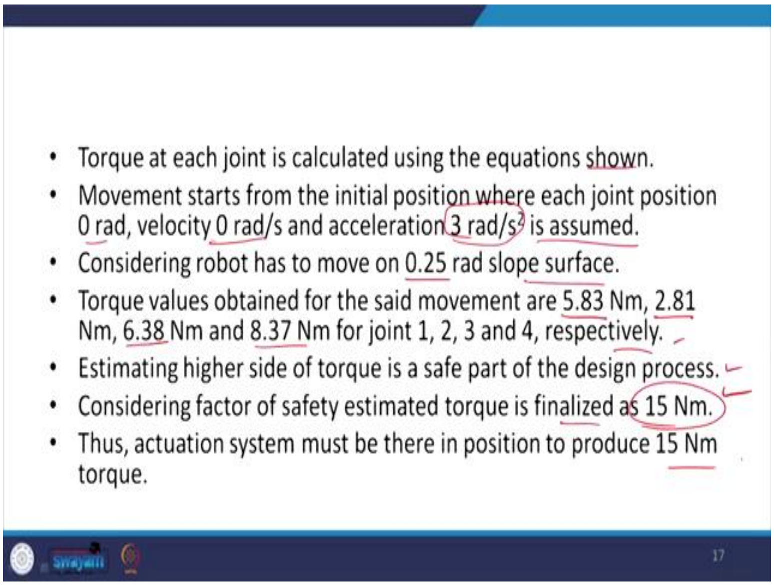
So, that is there, and then the torque applied at the front leg that is the link 1.

(Refer Slide Time: 13:42)



This τ_3 can be evaluated like this, and torque applied at the front leg that is of the link 2 this τ_4 can be evaluated. So, we have evaluated these four torques τ_1, τ_2, τ_3, and τ_4Where the actuators are placed.

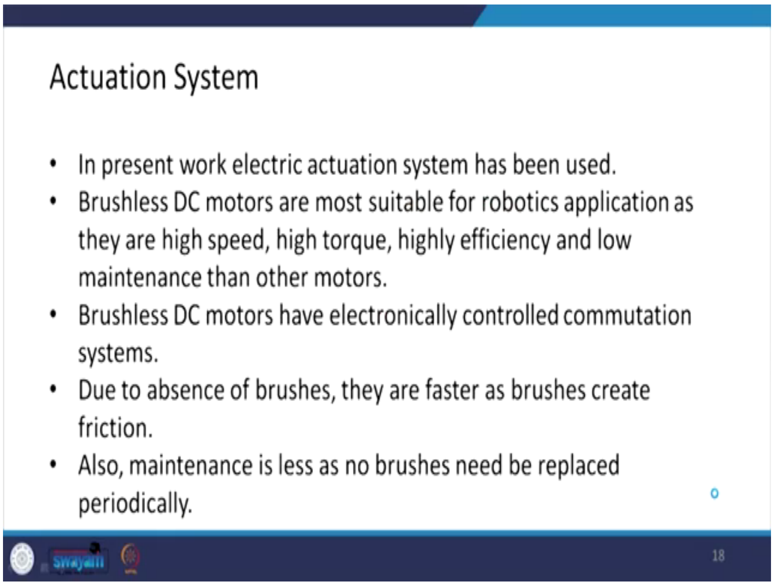
(Refer Slide Time: 14:05)



So, the torque at each joint is calculated using the equation shown as we have seen previously. The movement starts from the initial position where each joint position is at 0-radian velocity 0 radian per second and an acceleration value we have assumed that is 3 radian per second square is this value has been assumed.

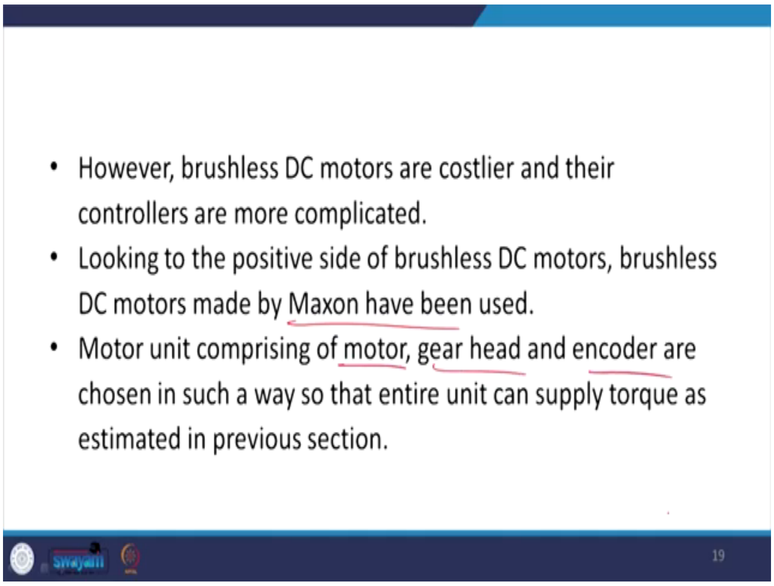
We have considered that the robot moves on this inclination radial slope, and then we calculated these torques values. So, 5.83 Newton meter, 2.81 Newton meter, 6.38 Newton meter, and 8.737 Newton meter for joints 1, 2, 3, and 4, respectively. Now, estimating a higher side of torque is a safe part of the design process. We considered a certain factor of safety, and we took torque as 15 Newton meters. So, the actuation system must there be able to produce this much amount of torque.

(Refer Slide Time: 15:17)



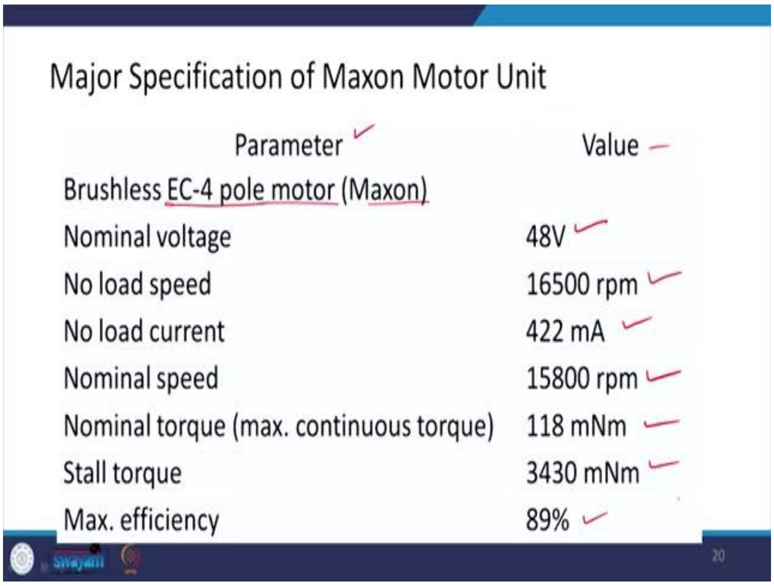
Next is the selection of the actuation system. For making a compact actuation, we are using the electrical actuation system, and for that, we use the brushless DC motor more stable for robotic application as they have high speed, high torque, high efficiency, and low maintenance than other types of motors. And these brushless DC motors have an electronically controlled commutation system. Due to the absence of brushes, they are faster, and also, maintenance is less as no brush need to be replaced periodically. I have talked about this brushless DC motor in my electrical actuation lecture.

(Refer Slide Time: 16:20)



Now, these brushless DC motors are costlier, and their controllers are more complicated. So, that is one problem with them, but looking at the positive side of brushless DC motors, brushless DC motors made by the Maxon we have used and this motor unit comprises of the motor, the gear head, and the encoder. These units were selected such that we get the required torque.

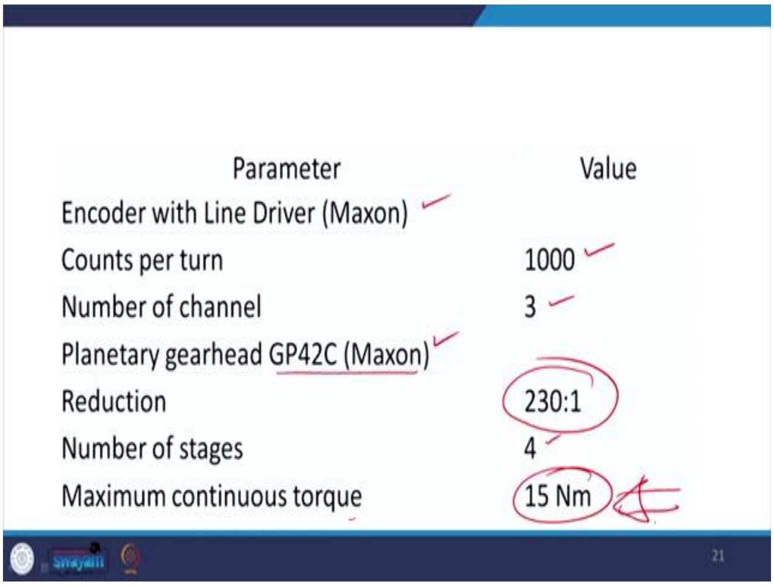
(Refer Slide Time: 16:58)



The major specification of the Maxon motor unit, which we used, in this case, is the parameter and values. So, we use the brushless electronic commutation four pole motor

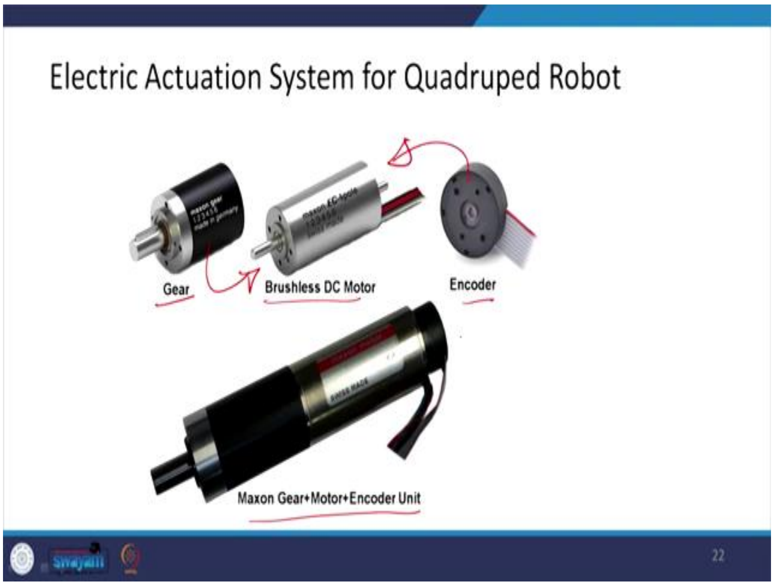
Maxon one voltage rank 48 volts, no-load speed 16500 rpm, and the no-load current is 422 mA. Nominal speed 15800 rpm, nominal torque 118 mNm, stall torque is 3430 mNm, and maximum efficiency is 89%.

(Refer Slide Time: 17:38)



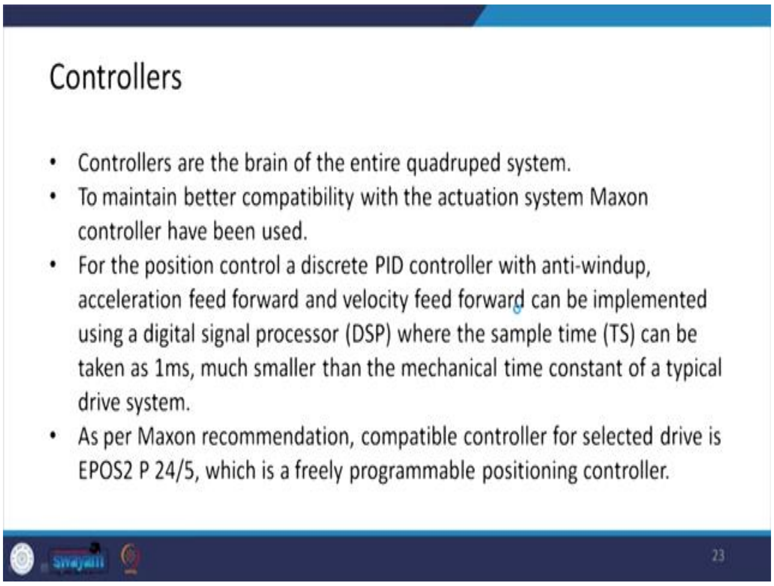
Here is the parameter for the encoder. So, encoder again with line driver Maxon we use the count per turn 1000 number of channels 3, planetary gear head this GP42C from the Maxon was used and see the reduction 230:1. There is an increase of torque 230 times, and there are a number of stages four, and the maximum continuous torque is 15 Nm. So, now you can see why we have gone with this gear head because, as I said here, we assumed this 15 Nm our requirement. So, based on that, we went with this gear head.

(Refer Slide Time: 18:37)



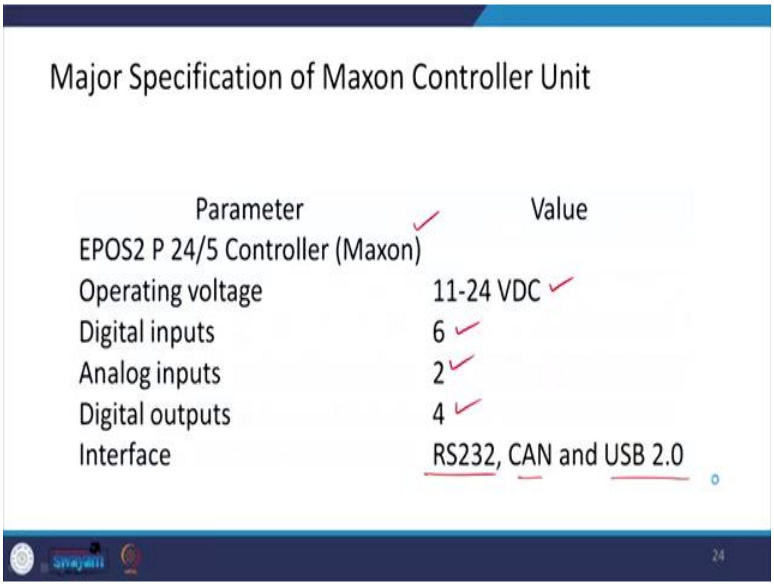
This was the electrical actuation system for the quadruped robot. The gear, brushless DC motor is here, an encoder is here, and this is how the entire assembly is. So, this is put over here, and this is put at the back, and this is how the entire assembly looks like.

(Refer Slide Time: 19:02)



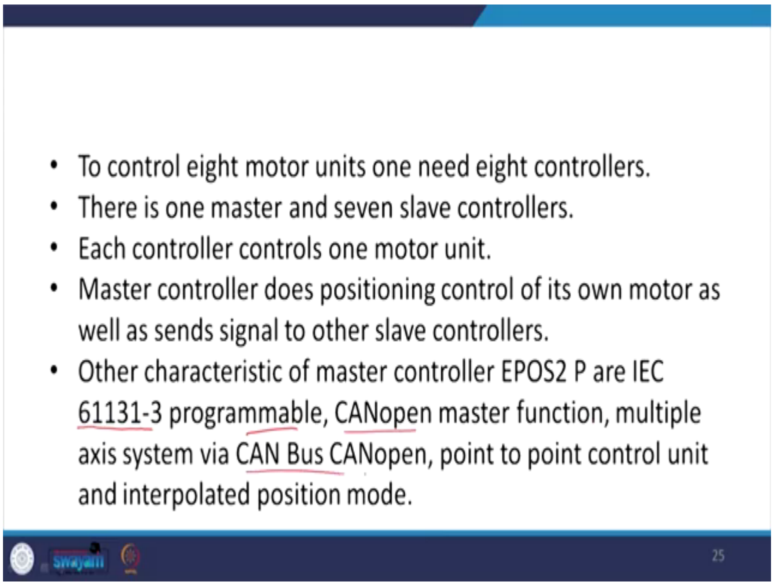
The next job was on the selection of the controller. The controllers are the brain of the entire quadruped system, and to maintain better compatibility with the actuation system, and we went with the Maxon controller only. For the position control, a discrete PID controller with anti-windup, acceleration feedforward, and velocity feedforward can be implemented using a DSP that is the Digital Signal Processor where the sample time can be taken as 1 ms, much smaller than the mechanical time constant of the typical drive system. As per the Maxon recommendation, the compatible controller for the selected drive is EPOS2 P 24/5, which is a freely programmable position controller which we used over here.

(Refer Slide Time: 20:13)



The major specification of the Maxon controller units that we used. This is the operating voltage 11 to 24 volt DC. There were 6 digital input channels, 2 analog input channels, and 4 digital output channels, and the interface was with the help of RS232 ports, CAN, and as well as USB 2.0.

(Refer Slide Time: 20:39)

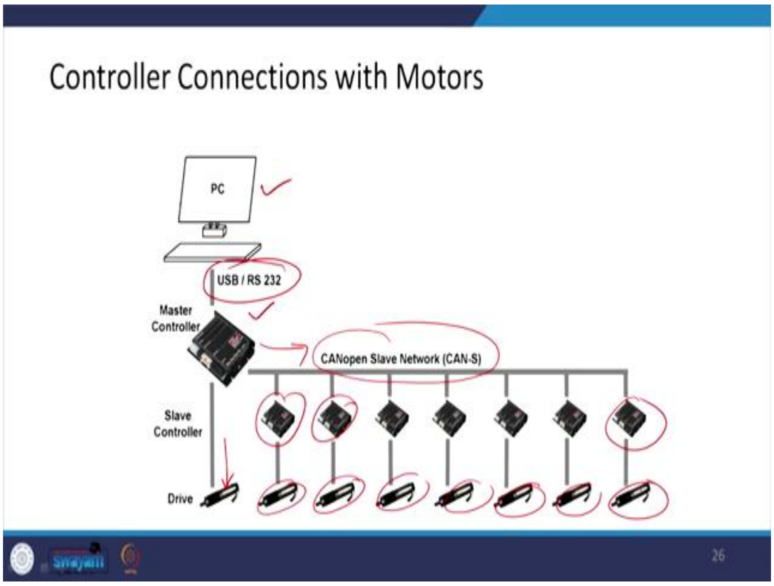


To control eight motor units, we used eight controllers, two in each leg. There is one master and seven controllers. So, out of these eight controllers, one can be treated as or converted as the master controller, and the other seven can be treated as the slave controller.

Each controller controls one motor unit, and the master controller does position control of its own motor as well as sends signals to the other slave controller. That way, it controls the other seven slave controllers.

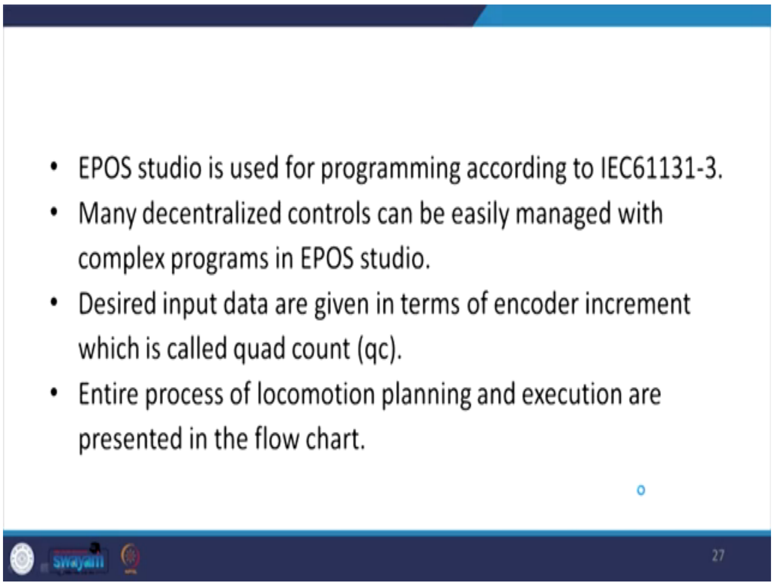
Now, other characteristics of the master controller that is EPOS2 P are IEC 61131-3 programmable, CANopen master function, multiple axis systems via CAN Bus CANopen, point to point control unit, and interpolated position mode.

(Refer Slide Time: 21:47)



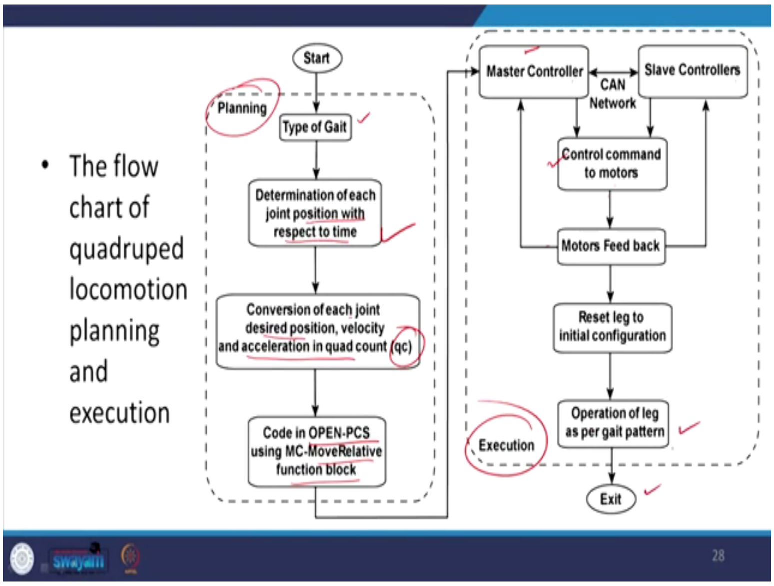
This is the structure of the controller connected with the motor, which you can see we had a PC there is USB or RS 232 port for the communication, we have the master controller, and there is seven slave controller connected to CANopen slave network CAN-S. And here are the drives. This master controller controls its own motor, and these send the signal to the other seven slave controllers. And these slave controllers, in turn, control these seven other motors. So, this is the controller connected with the motor which we used.

(Refer Slide Time: 22:33)



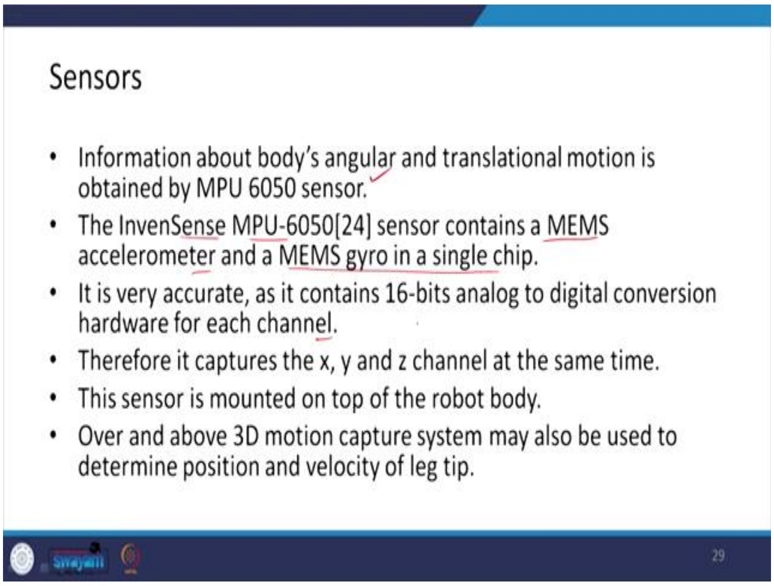
EPOS studio was used for programming purposes. Much decentralized control can be easily managed with the complex program in EPOS studio. Desired input data are given in terms of the encoder increment, which is called quad count, and the entire process of locomotion planning and execution is presented in the flow chart. So, this is how we planned and executed the motion planning for that.

(Refer Slide Time: 23:11)



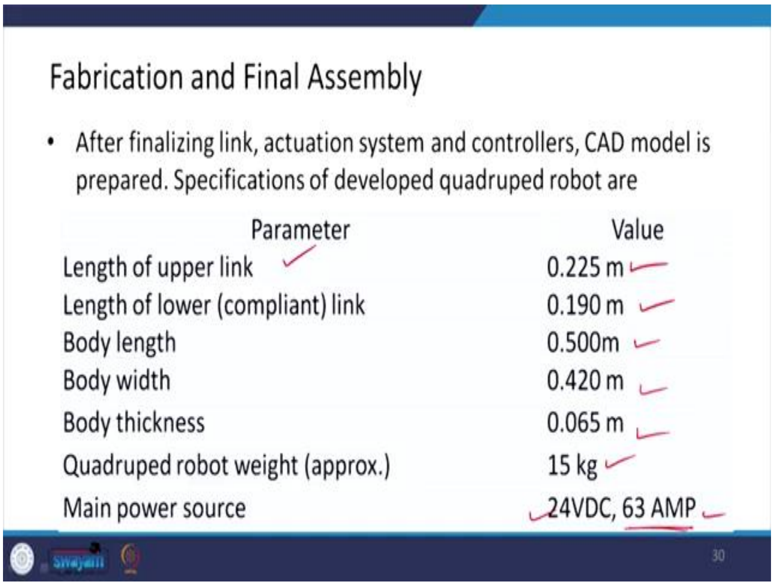
We start, and then we move to the what type of gait we are going our robot is going to follow, then the determination of each joint position with respect to time and the conversion of each joint desired position, velocity, and acceleration in the form of the quad count. Then the code in OPEN-PCS using MC-MoveRelative of function block and then it is sent to the master controller, and the master controller in turns communicates with the slave controller and so and master controller also gives the command to its own motor. The control command to the motor is given from the master controller as well as the slave controller over here, and there is motor feedback that can be given to the master controller as well as the slave controller over here. Then reset the leg to the initial configuration and operation of the leg as per the gait pattern, and then it exited.

(Refer Slide Time: 24:18)



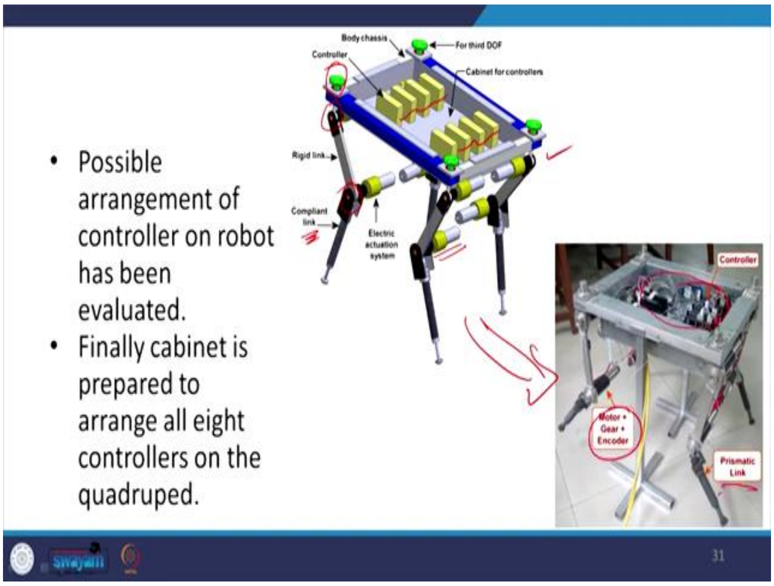
Now, let us look at the sensing part. So, the information about the body's angular and translational motion is obtained by the MPU-6050 sensor. The InvenSense MPU this one sensor contains a MEMS accelerometer and MEMS gyro in a single chip. It is very accurate, and it contains 16-bit analog to digital conversion hardware for each channel. Therefore, it captures the x, y, z channels at the same time. And this sensor is mounted at the top of the robot body, and over and above, the 3D motion capture system may also be used to determine the position and velocity of the leg tip.

(Refer Slide Time: 25:23)



Next is the fabrication and the final assembly. So, after finalizing the link actuation system and controller, the CAD model is prepared. The specification of the developed quadruped robots are following, so these are the length of the upper link, length of the lower link which is compliant body length, body width, body thickness, quadruped robot weight approximate it is of a 15 kg size and the main power source is a 24 volt DC and the power supply can give a current of the rate of 63 Ampere.

(Refer Slide Time: 26:05)

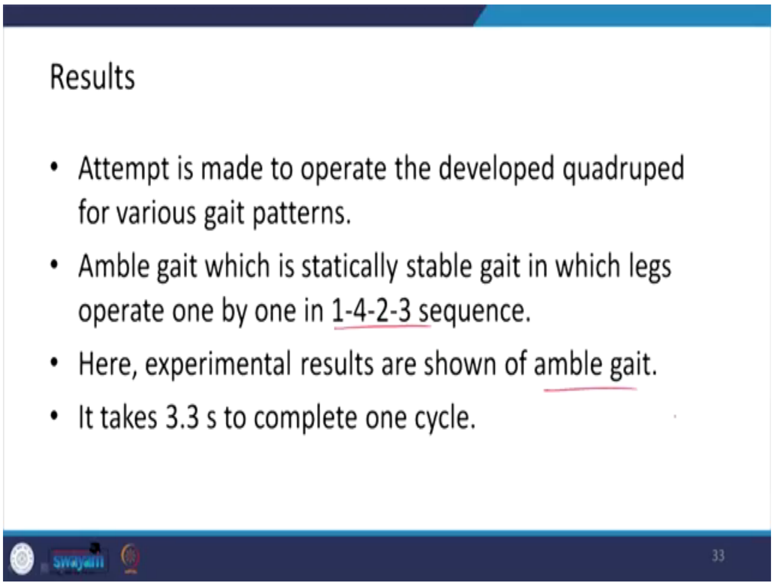


It is a solid works model. So, you have the compliant link over here, and these are the two joints. This is the extra joint that, in fact, we did not use. So, and these were all about the controller which was there, and here you have the actuator gear head as well as the encoder which is used as the sensor.

This one is the final, prepared model. As you can see, our controllers are placed over this one, and here is the unit for the motor, gear, as well as encoder, and this is the prismatic link. The pattern is prepared for hub and upper link, and they are cast from aluminum by the sand casting process, and their machine and final sizing were done.

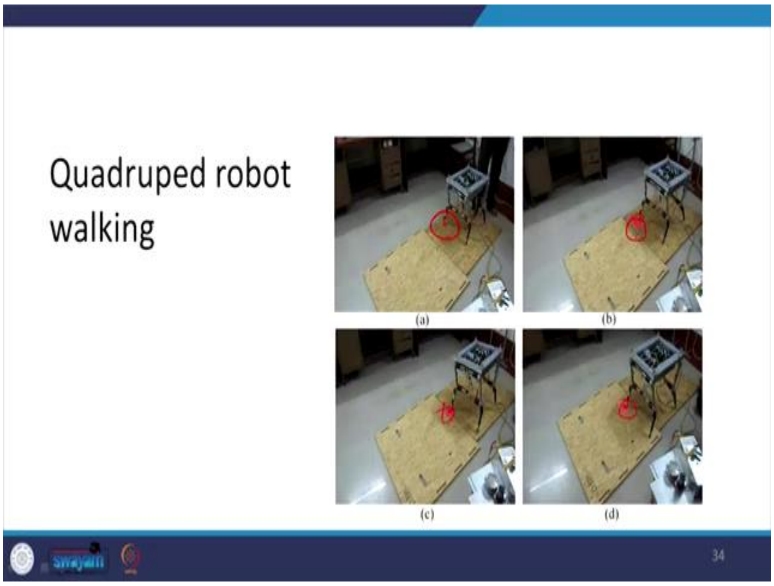
Robot chassis were prepared from the aluminum channel. The lower link, as I said, is a readymade purchase, and then it is modified by introducing a spring to get the compliance and cabinet is fabricated from the GIC.

(Refer Slide Time: 27:14)



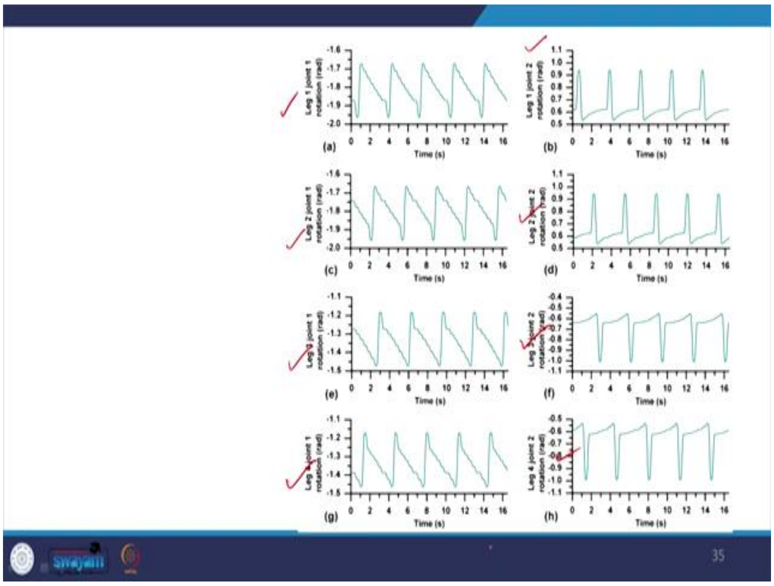
The results we attempt has made to operate the developed quadruped robot for various gait patterns. We carried out any type of analysis. You can look at the various publications from our group on the various results or the various test which we carried out. Amble gait, which is a statically stable gait in which legs operate one by one that is 1-4-2-3 sequence. Here are experiment results are shown for the amble gait, as I told you initially, and it took 3.3 seconds to complete one cycle.

(Refer Slide Time: 27:56).



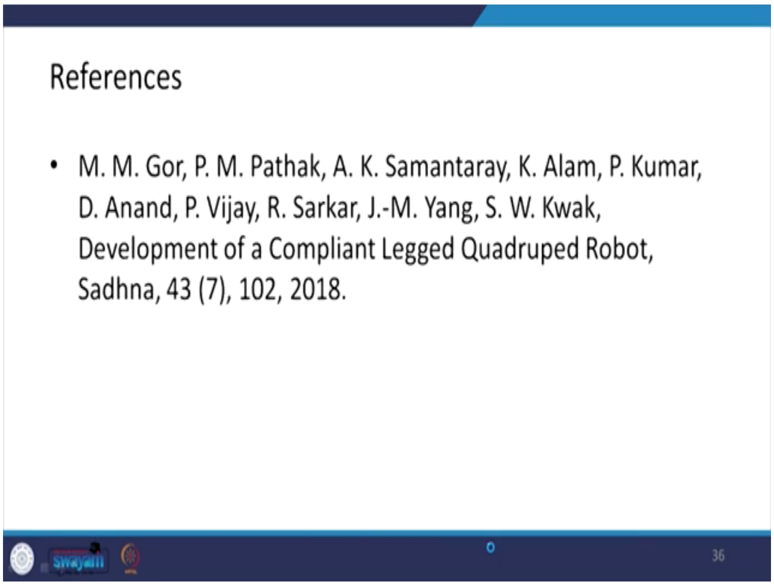
Here is the quadruped robot in the walking position. We put an indicator over here to just show the walking motion over there.

(Refer Slide Time: 28:09)



These are the plots. So, leg 1 joint 1, leg 1 joint 2. Similarly, leg 2 joint 1, leg 2 joint 2, leg 3 joint 1, leg 3 joint 2, leg 4 joint 1, and leg 4 joint 2.

(Refer Slide Time: 28:30)



If you want to look further into our work and make a similar type of bot, you can refer to our publication in Sadhna that is the development of a compliant legged quadruped robot.

Thank you.

(044) 2257 5905/08

nptel.ac.in

swayam.gov.in