**Wheeled Mobile Robots**
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**Lecture - 4.4**
**Commonly used sensors - 2**

Hello everyone, welcome back. So, we will continue the discussion on Sensors. In the last lecture we discussed about few sensors which are very commonly used for dead reckoning of mobile robots. We talked about the optical encoders which are used for position sensing as well as the RPM sensing in order to identify the distance travelled by the robots using the encoder.

And we also talked about the heading sensors, the compass and the gyroscope and we talked about how gyroscopes are constructed, the mechanical construction of gyroscope and the MEMS based gyroscope also we discussed. So, in this lecture we look at few other sensors which are again very commonly used and which are most likely familiar to you also.

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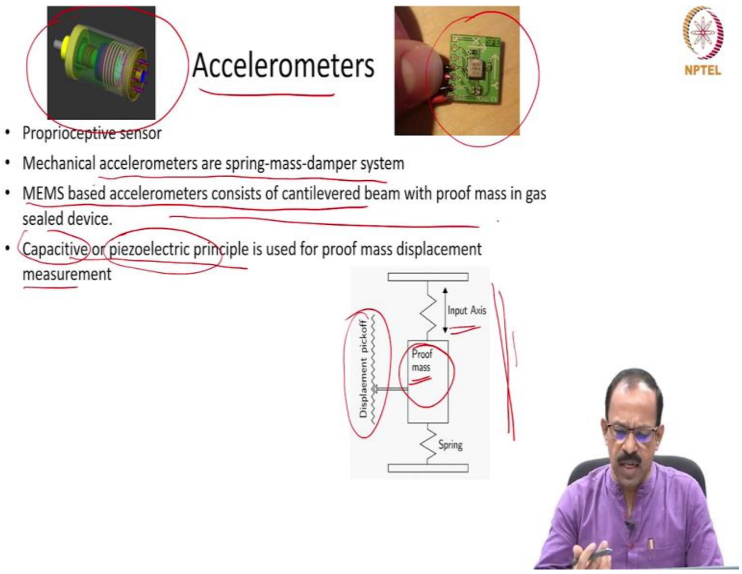


So, we look at the first one we will look today is the accelerometer. Accelerometer is a very commonly used sensor. It is not only for mobile robots. Nowadays, you will see that very small size accelerometers are there in lot of electronic devices. Even your mobile phone will be having an accelerometer, your laptops are having accelerometers nowadays in order to protect it from sudden fall and then consequent damages.

So, it has become a very commonly used sensor. It is basically a proprioceptive sensor in the mobile robots because it tried to find out the internal velocity of the robots through by measurement of acceleration. And the mechanical accelerometers which are the oldest type of accelerometer they are like a spring mass damper system. As you can see here in this diagram there is a proof mass which is suspended using a spring or there are two springs which are which is actually the spring the spring mass or the proof mass is suspended between these two springs.

And then whenever there is an acceleration of the body or the whole system there will be a displacement of the mass. And as you know F is equal to ma. So, whatever the force acting on the system will cause it to accelerate and that acceleration it can be measured as a eh displacement of the mass. So, the displacement of the mass is proportional to the acceleration and therefore, by measuring the displacement you will be able to get the acceleration of the body. So, that is the basic principle of a spring mass based accelerometer.

And we have this MEMS based one also. MEMS base is the micro electromechanical system. So, they are actually cantilevered beam with proof mass in a gas sealed device. So, again the principle is almost the same, but the mass is cantilevered and then it is kept in a gas sealed device.

So, any displacement of this mass is a measure of the acceleration of the body. So, that is the principle of MEMS based accelerometers. And the capacity or piezoelectric principle is used for the proof mass displacement measurement. So, how do you measure the displacement of the mass?

You can actually use a capacitive principle or an inductive piezoelectric principle to measure the displacement and that displacement because the displacement is very small. You cannot measure it using direct method.

So, you need to go for an indirect method of capacity change of capacitance or some piezoelectric effects because of the change in the position of the mass. So, that can be used for measuring the displacement. So, and then this displacement can be a measure of the acceleration.

So, that is the basic principle of the accelerometers. So, the mechanical type accelerometer which is basically the spring mass damper system. It will be like this. Its big size compared to the current generation of MEMS based accelerometers which are very small in size. You can actually see it in a chip and the principle is this one which is the cantilevered beam with a proof mass in a gas sealed device so that is the principle of accelerometer.

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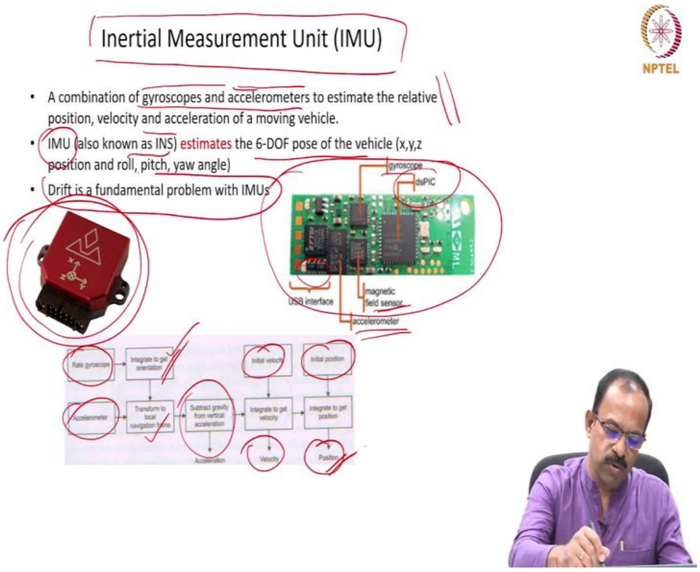


Now, coming to the inertial measurement unit which is the commonly used device or the sensor in most of the robotic devices and mobile systems which actually consist of a combination of gyroscopes and accelerometers. So, we know that accelerometers actually measures the velocity and gyroscopes can actually give you the orientation or the rate of change of orientation.

So, together these two so, accelerometers by measuring the acceleration you can get the velocity and by knowing the velocity you can actually calculate the position by integrating the velocity. Similarly, the gyroscope will give you the orientation or rate of change of orientation. So, together these two will provide you the complete pose of the robot that is the position and orientation of the robot can actually be obtained using this device and that is the inertial measurement unit or IMU.

All the robots nowadays use IMUs and as I mentioned not only for the robot there are many other systems which use IMUs for getting the position and orientation variation or changes in the position and orientation as the time progresses. Sometimes it is known as INS; Inertial Navigation System ok. So, all the inertial navigation system basically consists of IMUs; Inertial Measurement Units and that gives you the 6 degree of freedom pose of the vehicle.

That is you can get the xyz position as well as the orientation roll pitch yaw can be obtained using this IMU, simply by measuring the acceleration as well as measuring getting the orientation using the gyroscopes. And as you can see here so, this is a; this is a IMU which is commercially available one. So, you can see the axis are marked here. So, there will be accelerometers in all the 3 if it is a 3 axis measurement system and then you will be having accelerometers and gyroscopes in all the 3 axis.

So, the change in acceleration in about a particular axis and the change in orientation with respect to the particular axis can actually be obtained using this kind of a device. So, you place this on the robot and align the axis of the robot with the IMU axis then you will be able to get all the accelerations as well as change in orientations and you will be able to process it and get it get the done. So, the internal chip will be something like this. Of course, you can have different ways of arranging it.

So, you can see that the gyroscopes are there then the additional magnetic field sensors also will be there and then you have the accelerometers. And there will be the chips for processing these signals and finally, the using an USB interface you can connect this to your computer and then measure get the data directly from the PCB.

As you can see here there is a red gyroscope and accelerometer. And then rate gyroscope you integrate you get the orientations and then you transform it to the local navigational frame ok. That is basically if you have a change in the coordinate frames, you can actually transform it using the coordinate frame transformation.

And then accelerometer will give you all the accelerations and then you subtract gravity from vertical acceleration because always there will be this gravitational acceleration will be acting on the sensor. So, you subtract that to get the acceleration along the direction of the vertical axis. And if you know the initial velocity and the initial position you will be able to integrate the velocity and get the position by integrating the velocity information. So, you have the position and you have the orientation also. So, the position and orientation can be obtained using the inertial measurement units.

And this is an important sensor used in all the mobile robots. Of course, drift is a fundamental problem with IMUs is mainly because of the integration that you are doing. So, you are actually getting acceleration signals and then you are integrating the acceleration signal to get the velocity and then again integrating the velocity to the to get the position. So, any small error in the acceleration will actually project it as a big error in the position estimate. And this integration of errors will actually lead to large drift.

So, you cannot use it for a very long duration measurement, but for short duration measurements it is very good one and that becomes a very basic measurement unit in any robot. So, as I mentioned you cannot really use only one sensor many times you may have to use additional sensors to correct the drift error in such sensors ok.

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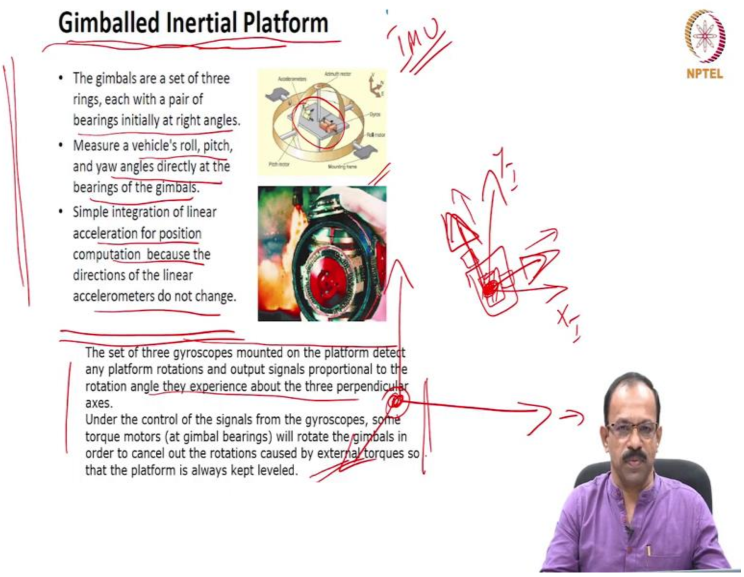


Now, how do we actually place this inertial sensors? So, there are two ways of doing it. One is by placing the sensors the sensor on a gimballed inertial platform. This is where you identify the orientation of the sorry identify the axis of the robot and then you have a inertial coordinate frame also. So, you have a fixed frame and a mobile frame.

So, you want to know the position of the robot with respect to a fixed frame. So, you fix this as an inertial frame and then you have a robot which will be having a frame of its own ok. So, this is the frame of its own. Now, all the measurements are with respect to the robot frame. So, you have the robot frame and then if you place an accelerometer in this axis and in this axis each one of this axis. What you are measuring is the acceleration along this axis and the acceleration along this axis.

But, we are interested is to get the position with respect to the inertial frame. So, if you are measuring like this then you need to convert that into this frame and then calculate the velocity and then calculate the position. So, there are two ways. One is that you measure this and then you calculate the velocities with respect to the inertial frame and then calculate the position.

The other one is you arrange the sensor on the robot in such a way that this robots the acceleration along the axis of the inertial frame is always measured. Whatever may be the orientation of the robot you try to measure the acceleration and velocity acceleration as well as the changes in the orientation with respect to the axis of the reference frame that is another way of doing that.

Then you do not need to do any conversion of or transformation of the coordinate frame or you do not need to transfer the velocity from the body frame to the reference frame. And this can be done by placing the IMU on a gimballed platform. So, what we do? We place the IMU in a on a platform on a gimballed platform by aligning the axis of the gimbal to the reference frame.

Now, whatever may be the change of orientation of the robot the IMU axis will always remain same because it is on a gimballed platform. So, any change in orientation of the robot will not affect the orientation of the IMU that is basically the gimballed inertial platform.

So, the gimbals are a set of 3 rings each with a pair of bearings initially at right angle. So, we saw this in the previous case of gyroscopes also. So, there will be a gimballed platform like this and the measure a vehicles roll pitch and yaw angles directly at the bearings of the gimbals. And then simple integration of the linear acceleration for position computation, because the directions of the linear accelerometers do not change.

So, once you place this on the gimballed platform, the IMU on the gimballed platform and if it is aligned initially with the reference frame then whatever may be the orientation of the robot any change in orientation on the robot, the gimbal will actually make sure that the IMU axis are always aligned with the reference frame. So, any measurement that you are getting is directly a measure along the axis of the reference frame. So, you just integrate that and then calculate the position.

So, that is basically the gimballed inertial platform. So, here the advantage is that you can you do not need to do a transformation of velocities from the body frame to the reference frame. So, the computation becomes much more easier in this case. So, that is why the gimballed inertial platforms are used in order to get the position and velocity position and orientation of the robot without having too much of computation.

So, as we can see here, so, you will be arranging the sensors on the platform and the sensors will be along the reference frame axis. And so, therefore, all the measurements will be with respect to the reference frame.

And of course, that the disadvantage is that you need to have a gimballed platform and so, it becomes mechanical structure and which need to be placed in a proper place and then you need to maintain that one. So, that is the disadvantage of using a gimballed platform.

But, the advantage is that your computational efforts will be much less in this case. Of course the other method is to have it on the axis ok. So, the three gyroscopes mounted on the platform detect any platform rotations and output signals proportional to the rotation angle by, the experience about the 3 perpendicular axes ok. So, that is basically how the implementation is done.

So, some torque motors will rotate the gimbals in order to cancel out the rotations caused by external torque so that the platform is always kept levelled. So, you need to have you need to keep all those I mean you need to have additional actuators to ensure that the rotations of the body or the robot are compensated using this motor.

So, that the axis is always maintained with the reference frame axis. So, that is what actually needed in the gimballed platform. So, this is having difficulty as you can see that you need to maintain the 3 gyroscopes in this case.

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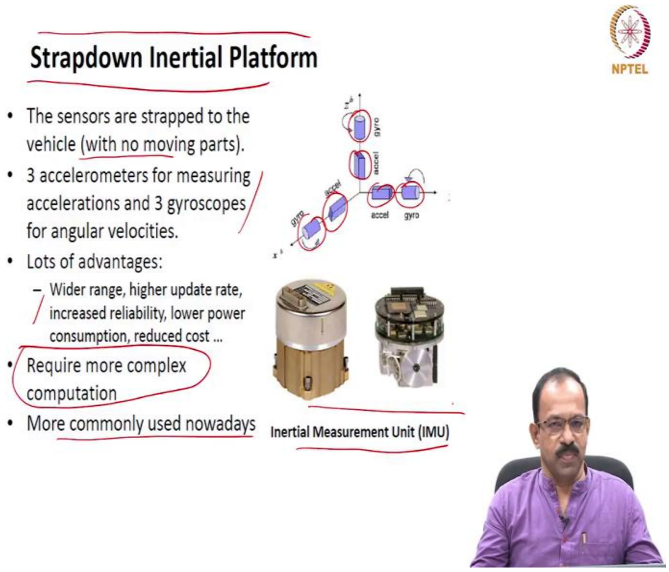


So, the other one so, an easy method is to have the strap down inertial platform. In strap down inertial platform what we will do? We will have this one accelerometer and one gyroscope along the axis of the robot. Each axis of the robot will have one accelerometer and one gyroscope. And it will measure the acceleration as well as the gyroscopic movement or the orientation changes or heading change can actually be measured with respect to the robot axis. And then what you do?

You just transform this to the reference frame body reference frame from body reference frame to the inertial reference frame and calculate the velocities and then calculate the change in position. So, that is what actually done in the strap down inertial platform ok. So, there are no moving parts.

So, 3 accelerometers are measuring acceleration 3 gyroscopes are measuring the angular velocities. So, it has got many advantages ok. So, there is not much of no additional actuators for maintaining the axis orientation and that is for low power consumption reduce cost etcetera. Only thing is that it require more complex computation.

So, you need to have more computation in this case because you need to transform the velocities in the inertial in the mobile frame to the inertial frame. And they are more commonly used nowadays considering the requirement of less power and less complexity strap down inertial platform is preferred compared to the gimballed platform.

So, that is the way how the IMUs will be used in a mobile robot to get the position and orientation ok.

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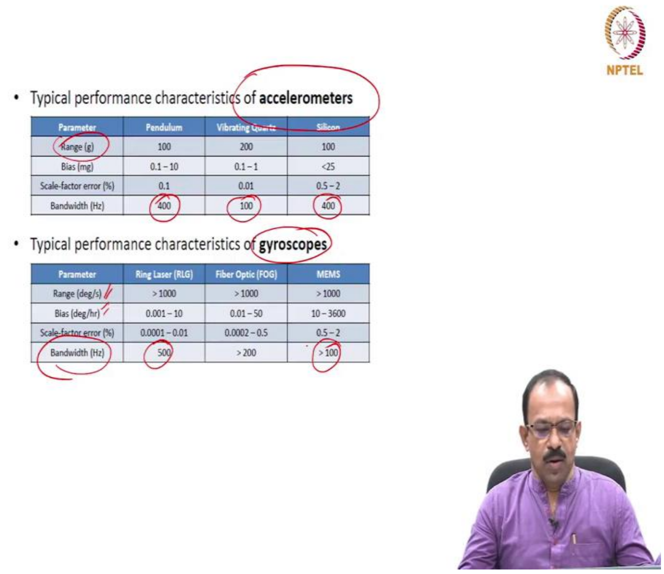


So, these are the typical performance characteristics. Of course, this keeps changing every year. You will be getting better and better one, but in general you can actually get a range of that is the vibrating quartz and then silicon. These are different types of accelerometers; a pendulum type of vibrating quartz or silicon type.

And you can see the bandwidth is around 400 in this case ok. Here also 400 Hertz. This is 100 Hertz. Normally, most of our applications 100 Hertz may be sufficient. Similarly for gyroscopes also you can see the range then the bias and then the scale factor and the bandwidth also here. So, you can see the bandwidth is of 500 and MEMS is more than 100, again which is quite sufficient for most of our applications ok.

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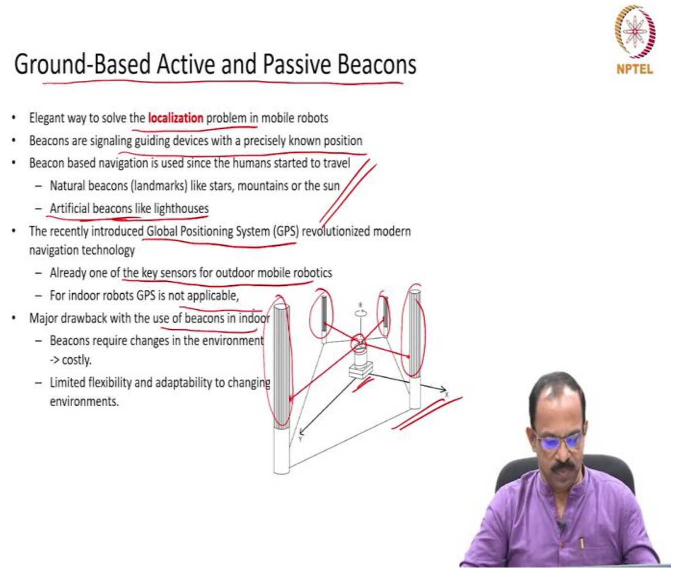


That was about the accelerometers and how the accelerometers and gyroscopes can be combined to get the position and orientation of a robot as the robot moves in a environment. And most of the time we use that one to get the position of the robot or to say we want to localize the robot or we find its current position, we use that method of dead reckoning, where we use the encoders or accelerometers and then try to find out the position of the robots. And we know that this will be having lot of errors or so, it may not be always correct as the robot starts moving.

After some time you will be having lot of drift errors and this will lead to changes in the actual position and the calculated position. So, many times we can use external means to get the position characters or we can use some other methods to get the actual position of the robot.

So, one of the commonly used method especially for indoor environment is the ground based active and passive beacons. So, we can actually have some beacons either passive or active in an environment and then get this information, get the signal from these beacons either using a I mean a sensor can be used on the robot.

And then it will be getting all the information from these beacons and by looking at the signals received from different beacons the robot will be able to calculate its position. So, you can actually localize itself based on the sensors which are external to the robot. So, that is the another way of getting the position of the robot and even its orientation also can be obtained by looking at the way in which the signals are coming from various beacons and how it is received at the robots.

So, its a good way to solve the localization problem in mobile robots. As I told you the localization issue though we can actually get the information using the proprioceptive sensors it will be having lot of drift errors. So, this is another way of good way of localizing the robots.

So, there are the signalling guiding devices with precisely known position ok. So, these are all at fixed positions. So, with respect to the environment their positions are fixed and therefore, once we know the position of the robot from that this fixed position the robot will be able to know where it is. So, that is basically the principle of beacon based localization.

And this is not a new idea it has been there for a long time. So, people are were using stars to navigate. So, by looking at the position of the stars there are methods to know the location of an object or a person and people use this in many other places like you know lighthouses. So, lighthouses are like artificial beacons that we where you are the ports you will see lighthouses.

By so, by looking at the lighthouse and the distance of the lighthouse the ships will be able to identify its location or the distance to the shore all those things can be obtained. So, that is basically application of beacons for localization. In olden times itself people are using this. And even birds will birds most of the migratory birds use the location of mountains to or the distance to the mountains to locate its position and then navigate and reach its target. So, it is a very well established methodology for localization.

And even your global positioning system which we call the GPS is based on this kind of this principle. So, we have many satellites which actually emit signals from different locations. And then at the receiver we will receive the signal from different the satellites GPS satellites and then using this information we will be able to know our position.

So, that is the basic principle of GPS based localization. And this is very commonly used in outdoor mobile robots, but of course, indoor we cannot really use it because the GPS data may not be available. But, outdoor the GPS based localization is a very very effective and very commonly used methods.

So, the basic principle is same the active beacons which emit signals and the signals are received at the receiver and then based on the received signals you identify the location that is basically the beacon based localization.

If you are using this in the indoor, the problem is that we need to establish the beacons in the indoor environment and their position also need to be known within the environment and that need to be provided the robot so that the robot will be able to localize.

So, there is need to have some changes in the environment and for an unknown environment you cannot really use it. This only for a known and well structured environment you can use it, otherwise you cannot really use it.

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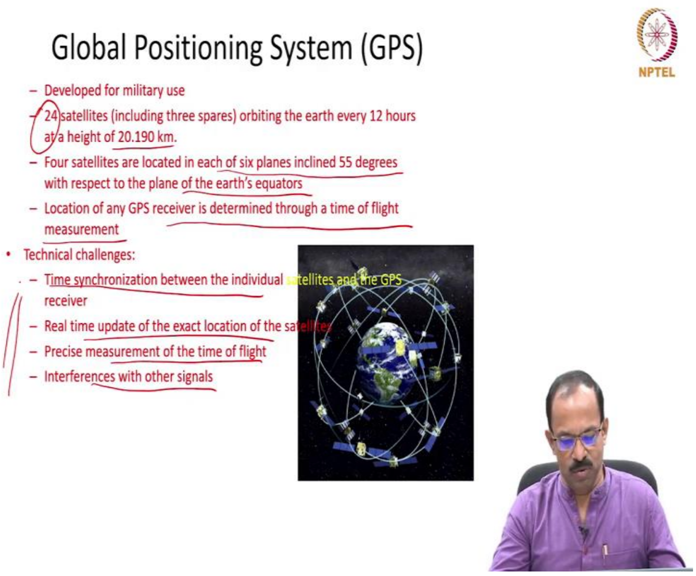


So, as I mentioned the global positioning system GPS is one of the very commonly used localization for outdoor robots. Of course, it is not only for robots even we use our in our mobile phone also we use GPS to navigate. So, we want to know our own location within a in a map we simply use the GPS data and then we look at the map and we try to position ourselves in the map using the GPS data.

So, how this GPS system works? So, there are 24 satellites, 24 satellites orbiting the earth every 12 hours at a height of around 20.19 kilometres. So, that is basically the satellites. And 4 satellites are located in each of 6 planes inclined 55 degrees with respect to the plane of earth's equator. So, there are four satellites 55 degree inclination and the location of any GPS receiver is determined through a time of flight measurements. So, now, all these satellites are emitting signals and if you can have if you have a receiver then we can actually get the signal from the satellite and we can find out the distance to that satellites.

And now, if we have more number of satellites by using the triangulation principle we will be able to find out our location. So, that is basically the principle ok. So, we need to have this time synchronization between the individual satellites and the GPS receiver. So, we need to have some kind of a synchronization between the receiver and the satellite ok, then only we can really calculate the time of flight.

And we need we can get the real time update of the exact location of the satellites need to be there and precise measurement of time of flight is an issue and the interference with other signals. So, these are some of the challenges, but we are able to overcome this and then get the location by overcoming these challenges of measuring the time of flight and exact location etcetera.

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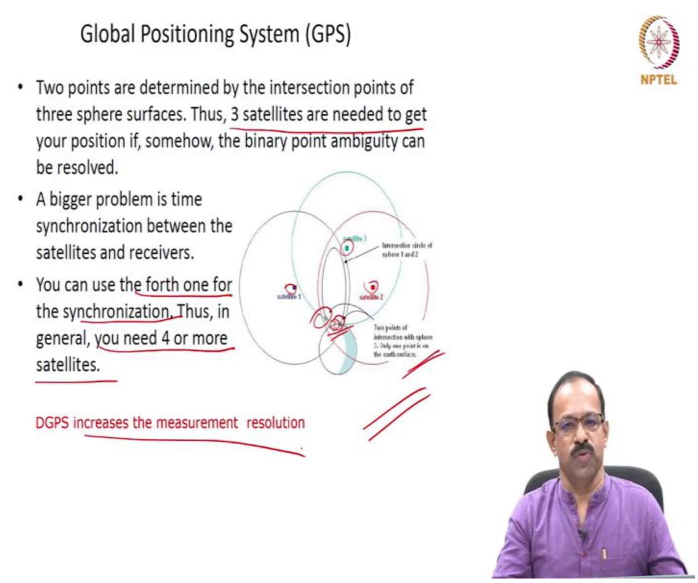


So, how is this done? So, as you can see here we need to have minimum three satellite signals to get our position that is for the position and one satellite is needed for the synchronization. So, with 4 satellites we will be able to get a we can we will be able to get our position with some accuracy ok. So, a fourth one for the synchronization is used.

So, in general you need 4 or more satellites. So, the principle is here. You can see that there are satellite 1, 2 and 3 and you will be getting the signal. So, if it is a receiver you are on the earth's surface you will be getting the signal from these three and by looking at these intersections you can have two positions. One is on the edge surface one is on the space.

So, by the ambiguity of this outer space position is once you resolve then you know there can be only one position where you have the all the three signals you are getting. So, that is the way how we can resolve the position of the receiver on the surface of the earth. Now, if you have more number of satellites you can get more and more accurate position because the there will be only one point which actually give you all the 4 or 5 or 6 satellites joining at one intersecting at one point.

So, you will be getting much more accurate positioning when you have more number of satellites. The minimum 3 satellites + 1 satellites for time synchronization, but the more number of satellites you will be getting more and more accurate positioning information. And this is why you see a big circle in your mobile phone? When you have a number of satellites are less the phone will say that your accuracy is very low. So, it will show you a big circle saying that you could be anywhere in this circle.

But, the more and more satellites you are able to receive then you will see that your accuracy will be much more much better, the size of the circle will start coming down and you will be getting a very accurate position of your receiver. So, that is the basic principle of a GPS based localization system. And it is a very commonly used method now and there are advanced systems also called DGPS; Differential GPS also.

When you have you want to have some millimetre level accuracies or the positioning you can use differential GPS to get the position more accurately. So, it re increases the resolution of the GPS ok.

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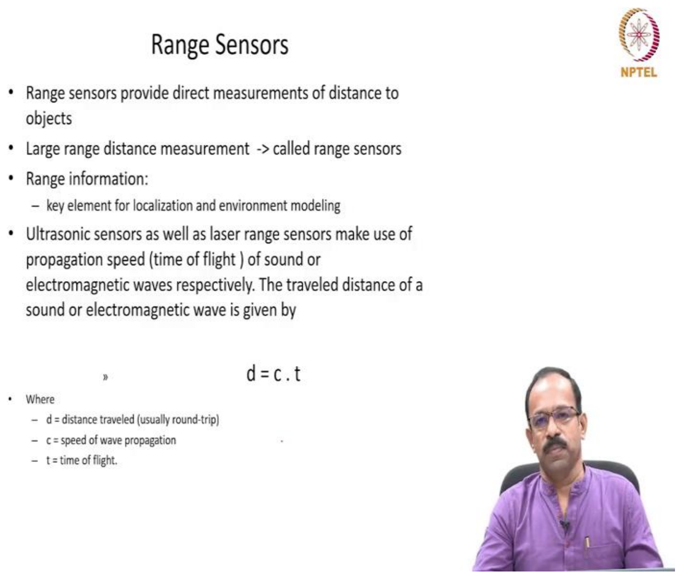


So, that is about the beacon based localization. So, that is one method of localization. Once you have an active beacon you will be able to get the signal from the beacons and the receiver can actually resolve the position based on the signals it receives ok. So, we will stop here I will continue the discussion on the sensors in the next class.

Thank you.