Robotics: Basics and Selected Advanced Concepts
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Lecture - 16
Sun tracking using 3-DOF parallel manipulator

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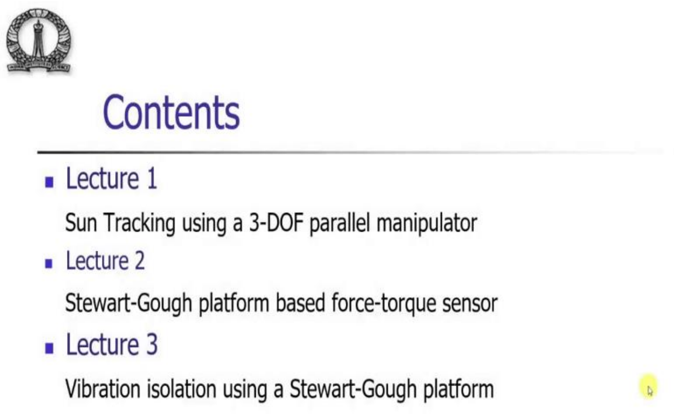

Welcome to this NPTEL course on Robotics – Basics and Advanced Concepts. In this week, we will look at applications of parallel robots. We had looked at the kinematics of parallel robots in the last week, now we will see some applications ok. So, there will be 3 lectures in this part.

The 1st lecture deals with sun tracking using a 3-degree of freedom parallel robot. In the 2nd lecture, we will look at Stewart-Gough platform based force torque sensor. And in the 3rd lecture, we look at vibration isolation using a Stewart-Gough platform ok. So, the 3-degree of freedom parallel manipulator and the Stewart-Gough platform is also a parallel manipulator, and it is one of the most well-known parallel robots.

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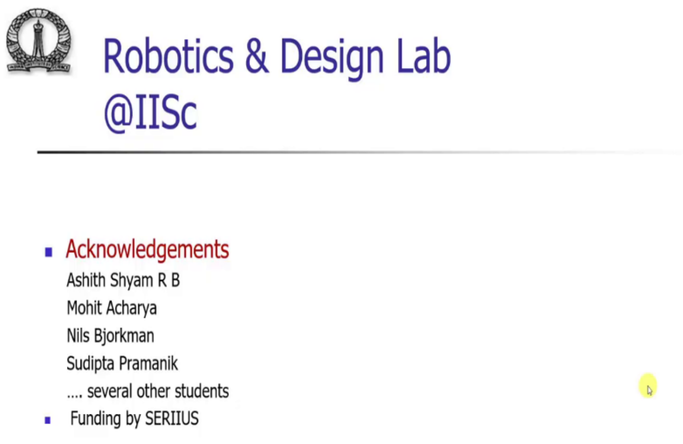

So, quick acknowledgement, most of this work was done by my students in the Robotics and Design Lab. So, there is Ashith, there is Mohit, there was a visitors from Sweden name of Nils, and then Sudipta and various other students ok. The funding came from this Indo-US project called SERIIUS ok.

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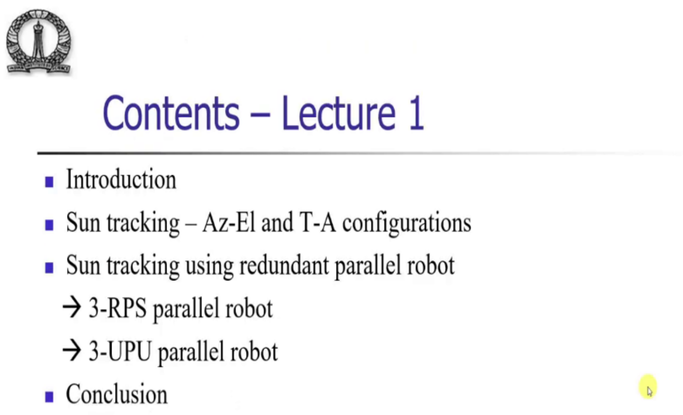

So, the contents of lecture-1, we will just introduce sun tracking initially then we will see some of the main standard configurations which are used for tracking the sun. Then I will follow how we can also track the sun using a redundant parallel robot and then conclusion.

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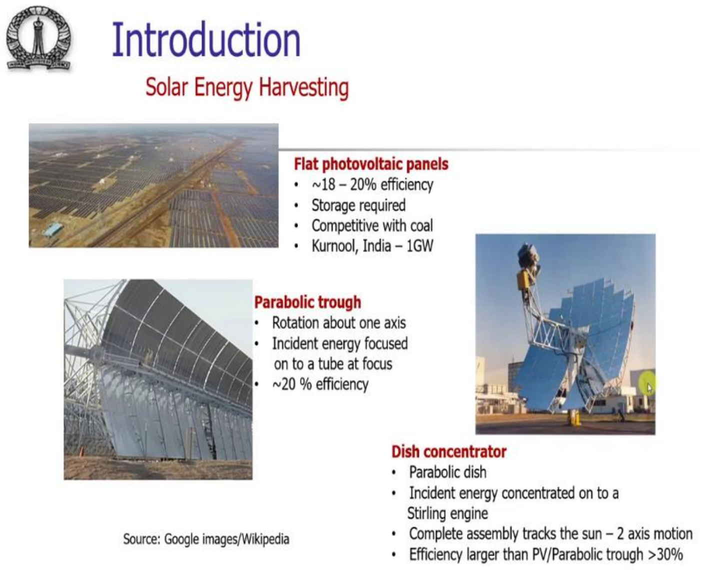

So, let us start, ok. So, solar energy harvesting is a very very important and upcoming field ok. We need to generate clean energy. We do not want burning coal, gas, because it is causing global warming; we are increasing the percentage of carbon dioxide in the environment which leads to global warming and various problems in climate.

So, solar energy is one of the cleaner source of energy. To harvest this solar energy and convert it into something useful form, there are various approaches. One is this thing called flat photovoltaic panels ok. So, basically this is a picture which shows that there are this huge field of panels – PV panels which are laid out in the field ok. So, they will convert the incident solar energy to electricity directly.

They typically have efficiency are of the order of around 18 to 20 percent, although there are some newer ones which have higher efficiency. One of the problems of solar energy is that you need to store the energy when too much is produced ok. So, in this PV panel, you need to store the energy using batteries or some other form, because when the sun is not there you still need to supply energy, and then the energy from the storage medium is sent back to the grid.

PV panels and solar energy using PV panels is becoming very very competitive ok. It is almost the same price as coal. So, in this figure, this is a site in Andhra Pradesh in Kurnool, and it is rated to produce 1 GW of electrical power ok. We can also have another way to harvest solar energy. This is called as parabolic trough.

So, what happens here is the suns energy which is in coming on to this mirrors, they are reflected on to a central focus ok. So, in this focus or in this tube, there are this water or some fluid which is running ok. And the that fluid can be raised to a higher temperature, and then that steam or some other fluid is taken out, and it is used to run the generator ok. So, the tube is at the focus and as the sun moves this parabolic trough is rotated in the east-west direction. This has an efficiency of the order of 20 percent.

There is also something called as a dish concentrator. Basically, it is a dish which is in the form of a parabolic dish. And at the centre or the focus of the dish, there is a device ok which can convert thermal energy to electrical energy ok. So, most of the time, it is something called as a Stirling engine. So, the advantage of this is that this parabolic dish concentrator of this dish can track the sun in two directions. It can track in the east-west directions and it can also track the seasonal motion of the sun ok.

It also has much higher efficiency than PV or parabolic trough. You can have efficiency of the order of 30 percent. So, this is the efficiency of the incident energy to the amount of electrical energy that is produced.

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One more way of generating electricity from suns energy is something called as a concentrated solar power tower ok. So, the left hand side shows a picture of several lots of mirrors which are moving and focusing their energy onto a central receiver ok. So, unlike the parabolic dish, all this mirror energy coming onto the mirror and reflected comes to the central tower ok.

So, this is called as a power tower. And this is called concentrated solar power tower because all this energy which is coming in each of these mirrors concentrated at this receiver ok. So, as I have shown you this is many many mirrors are there, and they need to move to track the sun and the incident energy will go and hit this tower ok.

This is being implemented in many many places because of a few advantages. So, it has been implemented in Spain, US, Australia, Middle East, China, and various places. So, what is the setup? They have large number of mirrors; these are also called heliostats. They will track the sun and focus energy at a distant receiver ok. So, the distance between this central tower and the last mirror could be as much as 1 kilometre nowadays, ok.

Now, since there are so many of these mirrors which are focusing their energy onto a tower, the temperature of this receiver can go very high ok. It can go to 600 degree centigrade or even higher ok. And as a result since the temperature is high, the conversion of thermal energy to electrical energy is also more efficient ok. So, you can easily get more than 30 percent efficiency.

Another big advantage of this concentrated solar power tower scheme is that you can store the energy as thermal energy. So, you can have what are called as molten salts or some other way of storing the energy in a thermal form. So, when there is no sun ok, we can get recover that energy and continue to run the generators and power the grid.

The challenge in this setup is that the motion of the sun is very very slow ok. So, typically a sun moves of the order of 180 degrees in 12 hours in the east-west direction; and it also moves some 30-40 degrees depending on which latitude you are on in the north south direction.

The other big challenges, we need to make sure that we track this sun and point this reflected beam very very accurately. So, we have to track move this mirror very slowly, but at the same time very accurately. How much accuracy? Typically we need of the order of 5 milli radians.

Why? Because if you think of a mirror as let us say 1 metre by 1 metre, and this is 1 kilometre away and we can see that if you want to focus the beam onto some area of this receiver ok then if you are off then the reflected beam will go to somewhere else ok. So, typical accuracy requirements are of the order of 5 milli radians. So, the main challenges we need to move these mirrors in 2 axes very slowly, but very accurately.

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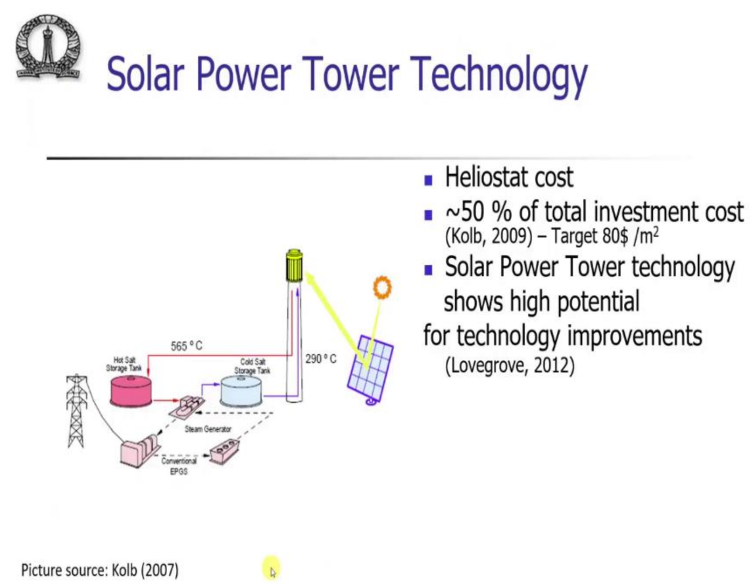

A typical setup of this solar power technology is the following. So, we have this mirror also called as a heliostat. The sun’s energy is reflected from the surface of this heliostat. It will go to a receiver ok. And typically this output of the receiver could be shown here at 565 degree centigrade, but it can be even higher. So, we store the energy in hot salt or storage tank then we convert that to steam by means of a heat exchanger ok.

And then we run a generator and convert it into electricity to feed into the grid ok. The output of this storage cold storage tank is much lower. And the after the receiver it is much higher ok. So, it turns out that the heliostat cost, it is a significant cost of this whole setup ok.

So, according to this researcher Kolb ok, it is of the order of 50 percent. And in 2009, he had said that we need to lower the cost of this heliostat to less than 80 dollars per metre square ok. So, in order to be competitive with cold and wind and various others forms of energy ok, he had said that it shows very high potential ok.

And this was another researcher’s in 2012, he claimed that this is much more potential than let us say PV ok, that may or may not have come true, but nevertheless it is a very challenging and very potential technology to convert suns energy into electricity.

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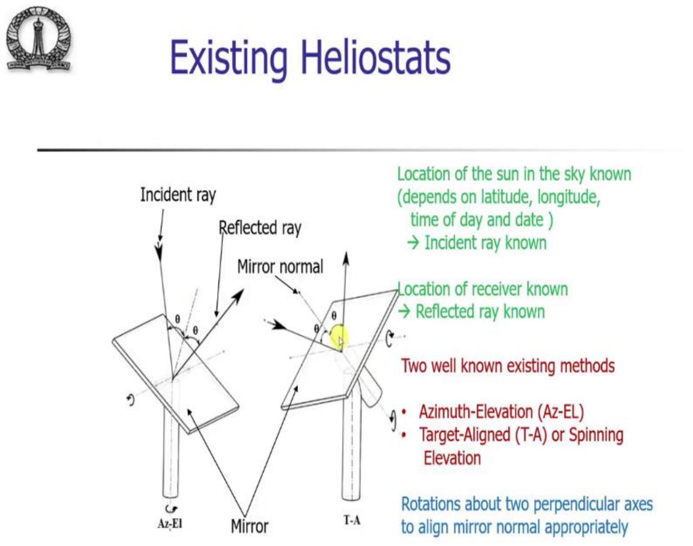

There are various existing heliostats. There is one which is called the azimuth elevation heliostats. So, basically it has 2 degrees of freedom ok. The sun moves east-west and north south, so you need 2 degrees of freedom or 2 axes motion. So, one motion is this azimuth – you can rotate by this; and there is other one is this elevation ok. So, sorry this is the elevation, and this is the azimuth.

So, what happens is the incident rays comes and it gets reflected according to the laws of reflection. So, this is the normal to the mirror ok. So, what do we need to do? As the sun is moving we need to rotate this mirror such that the normal is in between the incident ray and the reflected ray. The reflected ray is fixed right because the location of the receiver is fixed in the field. So, only thing is the incident ray direction is changing, and then we have to suitably change the normal to the mirror.

And there are these laws of reflection which says that these three normal incident ray and reflected ray should be in the same plane. And the angle of incidence should be equal to the angle of reflection. So, the location of the sun or the location of the incident ray is known. It depends on latitude, longitude, time of day, and the date in the year.

So, the incident ray is fully known ok. The location of the receiver is also fully known ok. So, hence all we need to do is change the mirror normal by doing these two motions such that the laws of reflections are satisfied. So, as I said there are two very common existing heliostat.

One is called this azimuth elevation which is this one. And you can also have something called as a target aligned or spinning elevation heliostat. So, in the target aligned, so one of the axis is always pointing to the target ok. So, both of these are basically rotations about two perpendicular axes ok.

So, it is similar to the Euler angles which we have looked at in the much earlier in this course. So, by doing these two rotations or by doing a sequence of two rotations, I can track the sun that is the basic idea.

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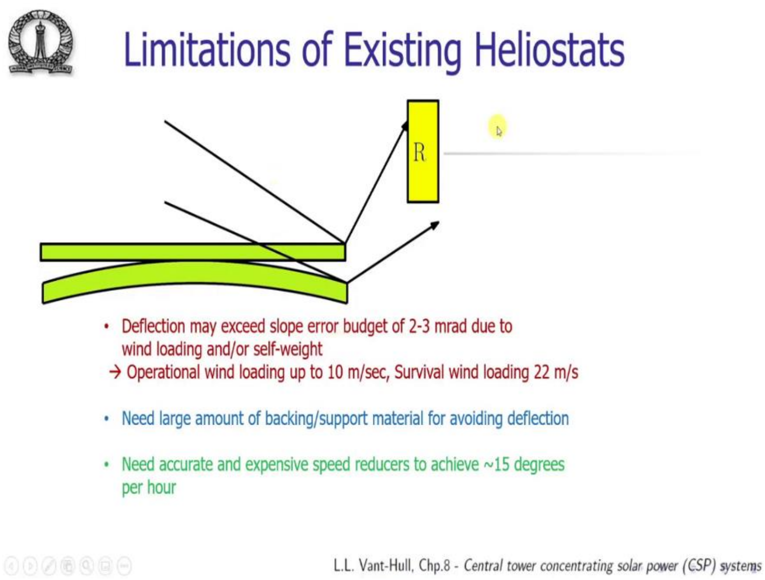

So, the limitations of existing heliostat, is that I cannot have very big heliostats ok. So, it is supported at one point ok. The azimuth and elevation axis there is one motor which is vertical axis, and one which is perpendicular to that. So, effectively the whole mirror is supported at one point ok. And the deflection due to wind loading or self-weight can be larger. So, there are limits on the deflection; we cannot have more than 2 to 3 milli radian due to wind loading or self-weight.

So, out of the 5 milli radian error budget, 2 to 3 is due to the wind loading and the self-weight deflection due to that. And we need to operate this heliostat up to a wind speed of 10 metres per second ok it should operate as if nothing is there. And it should be surviving up to wind speed of 22 metres per second ok. So, we need to design these heliostats such that these loading conditions can be satisfied ok.

So, if you have a single point contact, we need a large amount of backing or supporting material to avoid this deflection. So, as you can see in this sketch, if it is flat, it will go to the receiver; if the tip is bent due to this deflection, the reflected beam will go somewhere else ok. The other important challenge or existing heliostats is that we need very accurate and extensive speed reducers ok.

Typically, DC server motors as we have seen rotate best at something like 2000 rpm ok, but, however, we need the mirror to track 180 degrees in 12 hours. So, we need about 15 degrees per hour ok, remember per hour ok. So, hence we need a very very large speed reduction. So, simple calculation can show that the speed reduction should be of the order of 1 is to about 15000 ok.

If you make a gearbox with this kind of speed reducer either also maintain very good accuracy, we do not want too much backlash and friction and all those things which reduces the performance, then we it will become very expensive. And then we will not be able to compete with other sources of energy, which is also one of the reason.

Because of this gear reducers and motors and various other things the heliostat is one of the most expensive thing. All the heliostats together make up a large percentage of cost for solar field.

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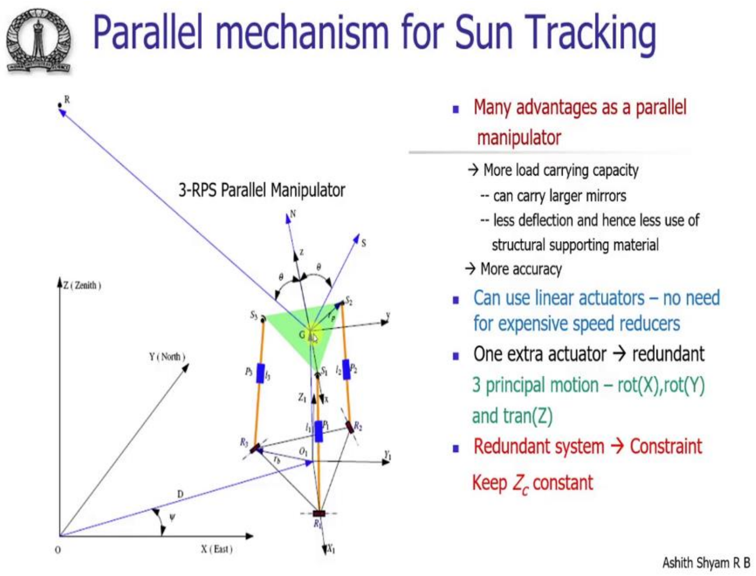

So, what we had proposed and one of the PhD students had proposed was to use a parallel mechanism for sun tracking ok. So, there are many advantages as a parallel robot. So, one of the main advantage of a parallel robot is it is supported at several places. So, hence it can carry more load ok, hence it can carry larger mirrors. And since it is supported at more than one point, it can deflect less. And hence it can use less supporting material structural supporting material.

So, what he proposed was a 3 degree of freedom 3-RPS manipulator. So, basically this is the top moving platform as we have seen about the 3-RPS manipulator. This is the top moving platform. The bottom platform is fixed. There are rotary joints at the base. And then there are the sliding joints at the each leg. And this S_1, S_2, S_3 are spherical joints ok.

So, we can use linear actuators ok, and we do not need expensive speed reducers. So, this P_1, P_2, P_3 prismatic joints are linear actuators which can give you this translation in this linear actuators ok. So, a little bit more of geometry. So, typically in this field the Z-axis is along the zenith. So, this is a fixed reference coordinate system which is X, Y, and Z-axis. The origin is at someplace in the field.

So, X-axis is typically always along the east, Y-axis is along the north and the location of the 3-RPS robot fixed reference coordinate system which at O_1, and X_1, Y_1, Z_1 is at a distance D and some angle ψ ok. So, these are the parameters that we require to model this 3-RPS robot for sun tracking.

Another important fact is there is one extra actuator ok. So, we have P_1, P_2, P_3 which gives you three different translations. However, we know that the sun tracking requires only 2 degrees of freedom ok, east-west motion and little bit north-south. So, there are 3 principal rotations; rotation X, rotation Y and translational along Z. The 3-RPS robot can be shown to the top plate can rotate about X and Y and it can go up and down. It can go up and down is very easily seen.

So, if I can move all these three actuators equally, it can go up and down. So, if I move two of them and do not move this, then it will rotate about some axes. And similarly, the if I move other two, it will rotate about some other axes. So, this is a redundant system as far as sun tracking is concerned. So, hence we need to make use of this redundancy.

So, what we do is we keep Z_c constant. So, Z_c is the location of the centre of the top platform constant ok. There can be other ways of making use of this extra degree of freedom, but in this case we had use Z_c as constant.

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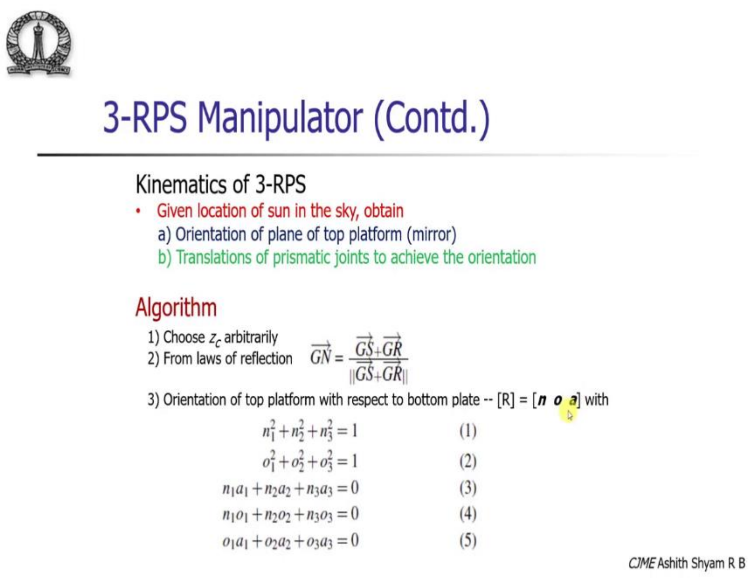

So, the kinematics of this 3-RPS robot was discussed little bit earlier briefly, but let us go over it once more. So, basically what we have is we are given the location of the sun in the sky. And what we want to do is, we want to obtain the orientation of the plane of the top platform or the mirror, and then we want to translate the joints to achieve the desired orientation ok.

So, what is the desired orientation of the top platform? Such that the incidence angles should be equal to the reflected angles, the normal should bisect these two rays ok, and hence we have to move the normal ok. So, the normal determines the orientation of this mirror. So, if I want to orient the mirror such that it obeys these laws of reflection we need to move the normal. So, the algorithm is quite straightforward ok. So, we choose Z_c arbitrarily because it is a redundant degree of freedom. So, we choose some value.

From the laws of reflection, $\overrightarrow{GN} = \frac{\overrightarrow{GS}+\overrightarrow{GR}}{||\overrightarrow{GS}+\overrightarrow{GR}||}$. So, $\overrightarrow{GN}$ is this vector $\overrightarrow{GN}$ ok. So, this is the centre of the top platform mirror, $\overrightarrow{GN}$ is the normal, $\overrightarrow{GS}$ is the vector towards the sun and $\overrightarrow{GR}$ is the vector towards the receiver ok. So, the laws of reflections says the $\overrightarrow{GN} = \frac{\overrightarrow{GS}+\overrightarrow{GR}}{||\overrightarrow{GS}+\overrightarrow{GR}||}$. So, again equal angles ok, the reflected beam and the incidence beam should make equal angle, and all three vector should lie in a plane.

The orientation of the top platform can be given in terms of X, Y and Z-axis in the rotation matrix. We are going to denote them by $[\boldsymbol{n}\ \boldsymbol{o}\ \boldsymbol{a}]$ok. So, $\boldsymbol{n}$ is one vector – X-axis; $\boldsymbol{o}$ is the same Y-axis, and $\boldsymbol{a}$ is the normal to the plane. So, we know that $n_1^2 + n_2^2 + n_3^2 = 1$.

So, basically is the unit vector, this is also unit vector. We also know that these three vectors form an orthonormal matrix ok. So, they are perpendicular; $\boldsymbol{n} \cdot \boldsymbol{o} = \boldsymbol{o} \cdot \boldsymbol{a} = \boldsymbol{n} \cdot \boldsymbol{a} = 0$;. And $\boldsymbol{a}$ is the normal to the plane ok.

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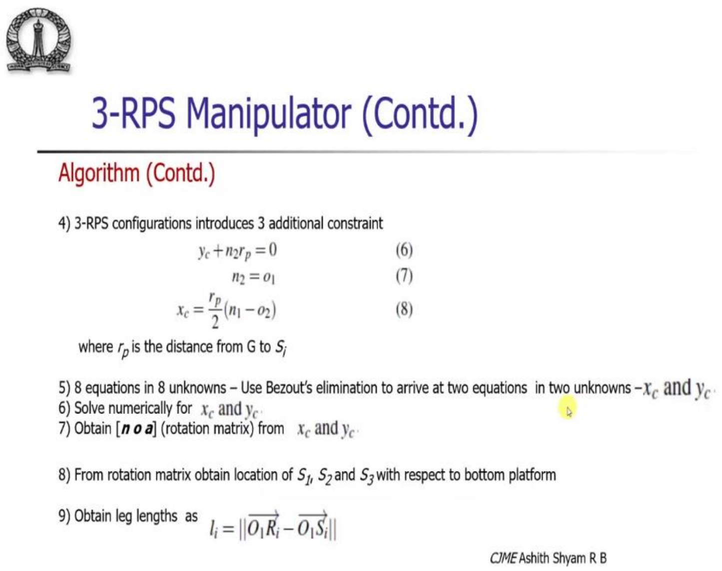

So, in this 3-RPS configuration, we also introduced 3 additional constraints. So, if you think about it, we can show that the y_c which is $[x_c, y_c, z_c]$ are the centre of the top platform. $y_c + n_2 r_p = 0$. So, what is r_p ok? So, r_p is some distance from the centre of the top platform to let us say the 3 S joints. So, here we are assuming that this forms a equilateral triangle.

So, r_p is this distance. Then $n_2 = o_1$; and $x_c = \frac{r_p}{2}(n_1 - o_2)$. So, you can think about it and we can see that it introduces these 3 constraints ok. So, basically what we have is 5 constraint equations from the axes of this rotation matrix; X, Y and Z-axis in terms of $[\boldsymbol{n}\ \boldsymbol{o}\ \boldsymbol{a}]$ with elements (n_1, n_2, n_3), and (o_1, o_2, o_3), and (a_1, a_2, a_3) and so on ok and three others.

So, basically we have 8 equations and 8 unknowns ok. Where are these 8 unknowns now? What are the 8 unknowns? So, basically we have 3 here – (n_1, n_2, n_3); (o_1, o_2, o_3), and (a_1, a_2, a_3), but (a_1, a_2, a_3) is the normal which we know or which we want, and then (x_c, y_c, z_c) ok. So, z_c is chosen constant ok. So, it is 6 of those from rotation matrix, and 2 – x_c and y_c, those are the 8 unknowns.

We use elimination theory to obtain 2 equations in 2 unknowns; x_c and y_c, and we solve numerically for x_c and y_c ok. So, once x_c and y_c is known and the elimination procedure is followed, we can back substitute and find out all the elements of the rotation matrix and the x_c and y_c ok.

So, once we know the elements of the rotation matrix and x_c and y_c and z_c is chosen, so then we can find the location of the 3 spherical joints S_1, S_2, S_3 ok. And then we can find the leg length because we know how much to move the leg length to achieve the location of the spherical joint. So, what is the leg length?$l_i = ||\overrightarrow{O_1 R_i} - \overrightarrow{O_1 S_i}||$.

So, let us go back and see once. So, this leg length will be $\overrightarrow{O_1 R_i}$. So, let us say $\overrightarrow{O_1 R_1}$ ok, minus $\overrightarrow{O_1 S_i}$. So, a vector from O_1 to S_1 minus O_1 to R_1 will give me this vector along the leg length. So, similar geometry and similar equations we have derived in the past for many parallel robots ok.

This is the way to locate the spherical joint and find the leg lengths ok. So, once we know x_c, y_c, z_c, and the rotation matrix, then we can find the spherical joints S_1, S_2, S_3, and then we can find the leg lengths which is this magnitude of the difference between these two vectors ok.

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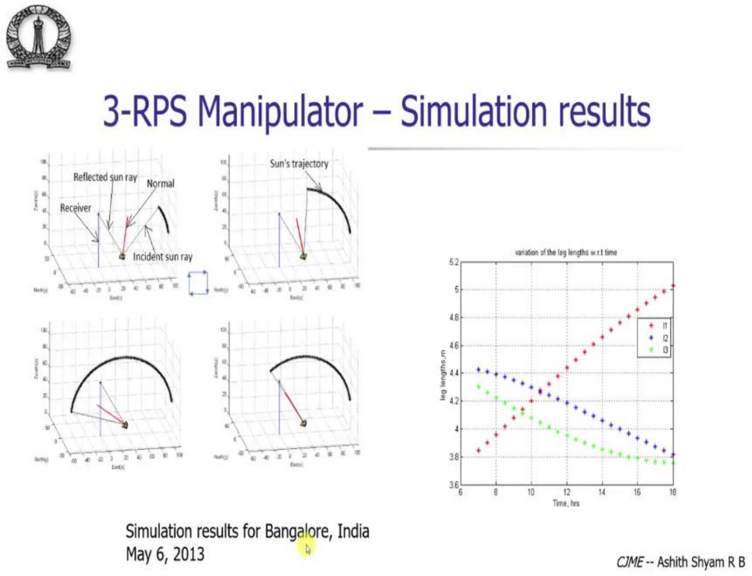

So, once we have this algorithm ready, we can do some simulation ok. So, these are the some simulation results for the motion of the sun and the values of the leg length for a particular day which is May 6, 2013 – 2013. Many others were done, but this is a nice picture. So, this is why I have chosen this. And then we can compute l_1, l_2, l_3 for this as the sun is moving.

So, here are four snapshots. One is the sun has moved from here to here. The red is the normal. The reflected beam which is fixed because the receiver is located fixed. As the sun is moving, you can see that the red the normal is changing ok, and hence the mirror orientation is changing. And for each of those instances, we can discretize this motion of the sun and then we can find out l_1, l_2, l_3 by that algorithm which I discussed just few slides back last slide ok.

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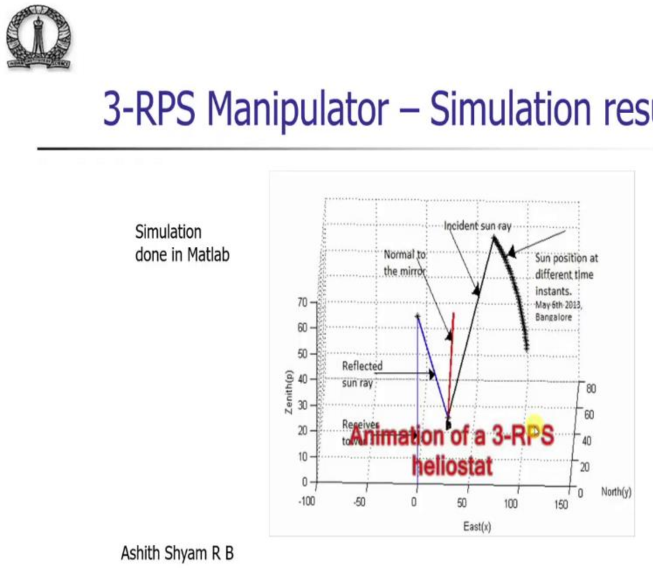

So, let us look at some simulation. So, these simulations were done in MATLAB. So, we compute all these quantities, we compute the normal, we compute the motion of this sun which is known just given.

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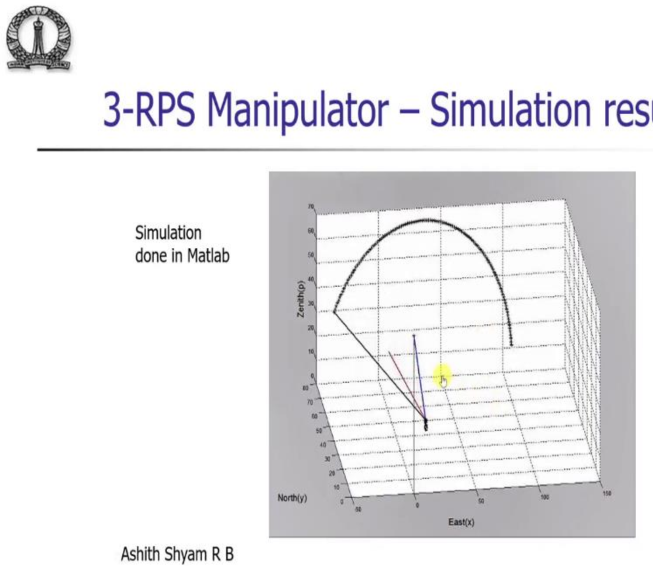

And then we show how the normal is moving ok. So, you can see that the blue is the reflected beam which is always constant.

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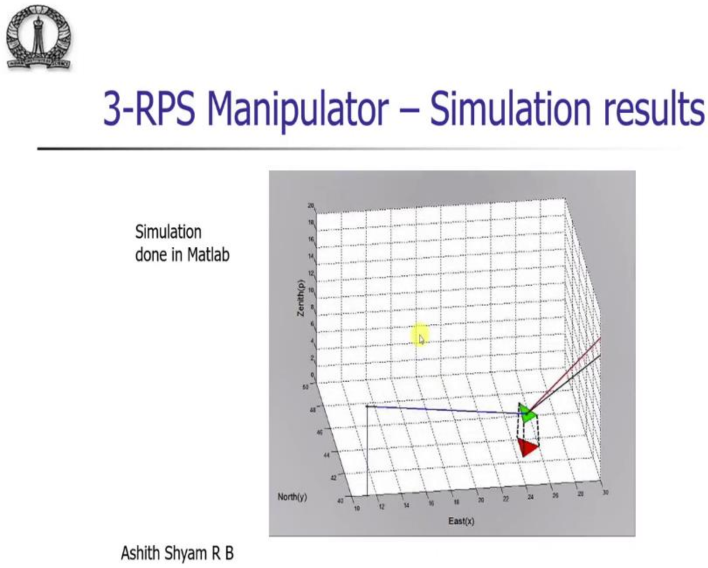

Red is the normal and the black is the direction of the sun. This is a more detailed picture. Zoom picture which says how the legs are changing ok as the sun is moving.

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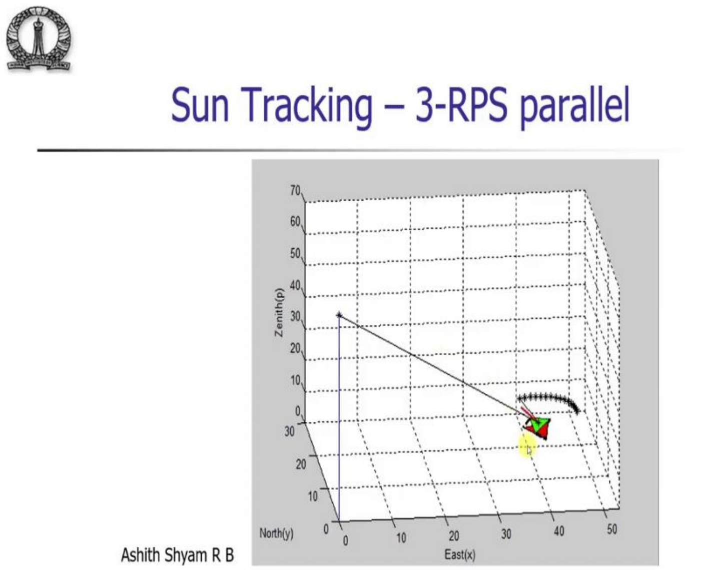

Another view of the thing that you can see that this is the mirror. This is 3-RPS robot how it is orienting when the sun is moving such that the reflected beam is at the same place.

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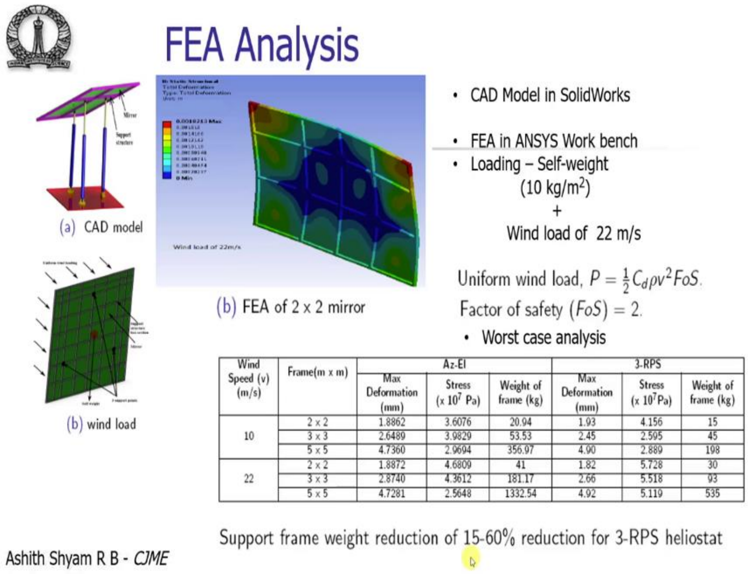

One of the things which I said was this parallel robot can take more weight ok because it is supported at three points. So, this analysis was also carried out. For this, we need to do a finite element analysis. So, we have a CAD model of this mirror and the three support points, and the backing structure in SolidWorks then we do this FEA.

So, we need to assume some weight of this mirror. It turns out this is of the order of 10 kg per metre square. The wind load is for the maximum load, we want to make sure that this mirror will survive which is 22 metres per second ok. So, this is the CAD model. So, we have these 3 legs. This is the mirror, and this is the support structure at the back. And the worst case is when the wind is coming directly normal to this mirror ok.

So, for a uniform wind load, the pressure $P = \frac{1}{2} C_d \, \rho \, v^2 \, FoS$; and we also do a factor of safety – in this case 2. So, we solve this problem for different wind speeds for different dimensions of this mirror. We took 2 × 2, 3 × 3, 5 × 5, and then we found what is the maximum deformation due to the wind and the self weight. And we also tried the existing azimuth elevation configuration which means basically it is supported at 1 point. And this 3-RPS configuration which means it is supported at 3 points.

So, what you can see is there are some deformations for 2 × 2 which is 1.8862 millimetres, whereas at 22 metres per second, it is 4.7281 millimetres this is the maximum deformation. In the azimuth elevation in order to meet that pointing accuracy requirement ok, we need to put a frame in the azimuth elevation which weighs about 21 kgs approximately for 2 × 2.

Whereas as the area becomes bigger and bigger ok, you can see that the supporting weight will become very large. So, this is like 1300 kg. The maximum deformation is such that it will still point to the mirror, point the mirror will still reflect the beam to the receiver. In the case of a 3-RPS robot, the weight does not increase so much ok. It is because it is supported basically at 3 points.

So, to achieve the pointing accuracy with a 3-RPS robot with wind at 22 metres per second, we need only 535 kgs of structural material ok. So, if it is a small mirror, it is 21 in azimuth elevation and 15. But if it is a large mirror – 5 by 5 metres ok, then we can see it the significant reduction. So, the supporting frame weight reduction lies between, 15 and 60 percent ok in the case of the 3-RPS heliostat.

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So, this mirror was designed, analysed, and then we built one such hardware one sun tracking hardware. So, how do we test it in the lab? So, for the azimuth elevation and also for the 3-RPS, basically what we did was we do not have the sun in the lab. So, what we do is we invert the problem. So, instead of the sun moving and the reflected beam at the same place, pointing at the same place or reflected to the same place, the sun here is stationary ok.

So, we have a laser which is pointing to the mirror which is this red spot. And then we move the mirror such that this beam follows some path on the roof. So, this path on the roof is basically the path of the sun ok on the particular day and time and so on. So, you can see these dots. So, these are the simulated or equivalent locations of the sun.

So, hence if I can move the mirror properly, it will get reflected onto this laser ok, the stationary receiver. So, let us see two videos. So, as you can see in this case this reflected beam is moving along the roof of the lab, and it should be approximately the place where the red spot is the location of the sun ok.

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So, we also manufacture the 3-RPS configuration. So, for the 3-RPS configuration, the spherical joints were basically spherical joints from some scrap or automobile shops. So, you can see they are not very sophisticated and fancy. The prismatic joints, these actuators were bought. And then we have some encoders, terminals at the base. So, we can measure the rotations of the motors which are implementing prismatic joints.

So, basically the prismatic joint has ball screws. So, we rotate the one of the items, and the nut will go up and down ok. So, we can measure the rotation of the ball screw by means of these encoder terminals.

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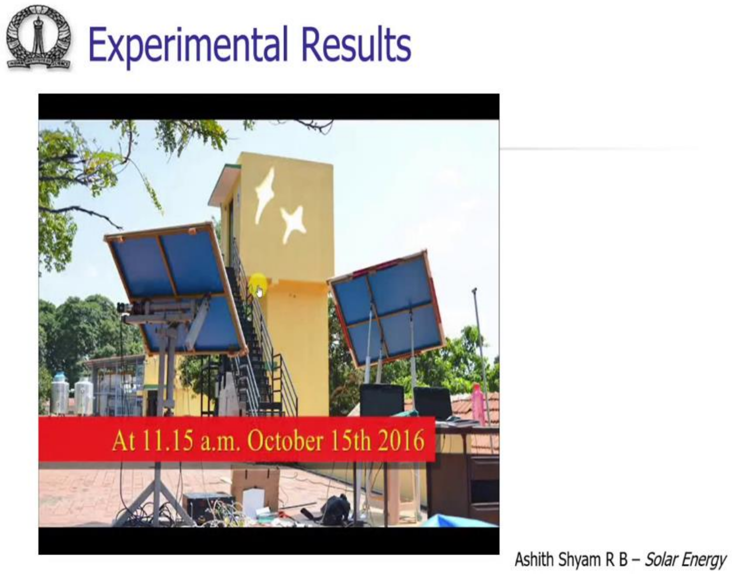

So, this is an experimental result, actual experimental result of the 3-RPS robot which was built and the azimuth elevation drive or heliostat which was built. And we can see how they perform.

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So, this is on some day at some time in top of the roof of one of the buildings in IISc.

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So, as you can see both of them are reflecting at some place ok.

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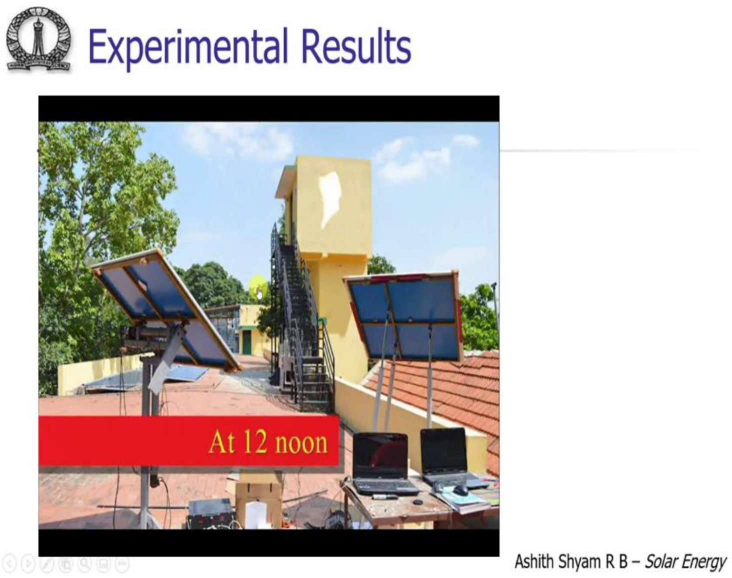

Ideally, they should be reflecting at the same place, but just to show that both are working we have just purposely made sure that it was focused on two slight close by spots ok. So, as you can see that the images are not exactly at the same place all the time. It should be in the actual field. And the problem is because of all the inaccuracies in manufacturing and control. So, now, you can see more or less at the same place.

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If it is cloudy, you do not see any image. So, at this place, at this point, you can see the two images are very close to each other.

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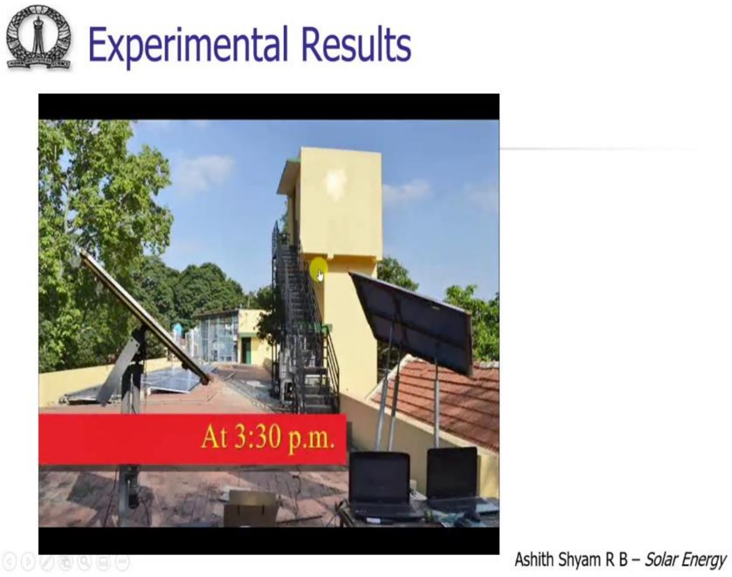

So, at 3:30 pm you can see both of them are at the same place ok. So, we tried this from morning till about 3:30 – 4:00 O' clock. But after that the sun goes down too much and you cannot focus the beam onto the receiver.

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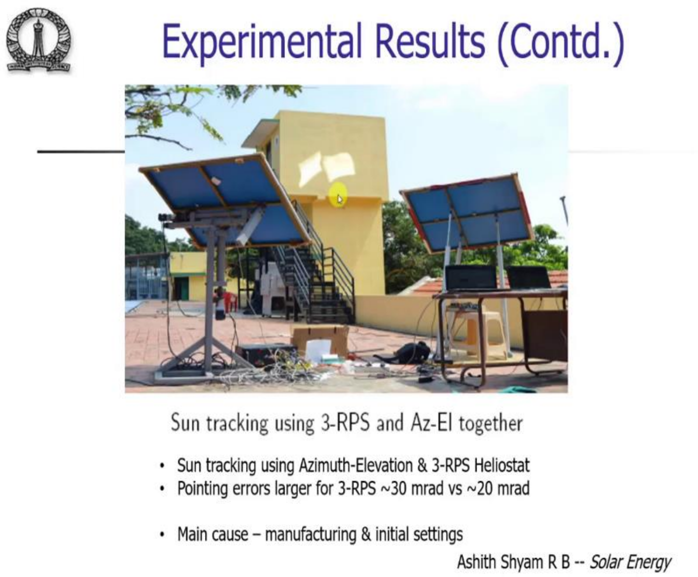

So, we build the sun tracking devices using a 3-RPS heliostat and an azimuth elevation heliostat. The pointing errors as you can see in the video are much larger than 5 milli radians ok. So, they are of the order of 20 to 30 milli radians ok. You should keep in mind that these are not professionally made heliostats. They were made by students. So, the main cause of this error are manufacturing and initial settings ok, which can be improved.

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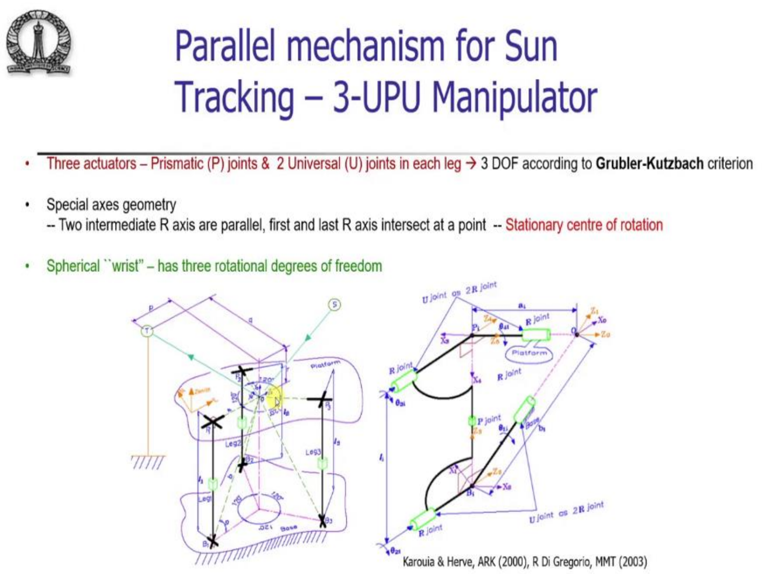

We can also build another parallel robot for sun tracking. And I will show you why we thought of building this parallel robot. This is this 3-UPU manipulator ok. So, previously it was 3-RPS. So, there is a rotary joint, prismatic joint and a spherical joint. In this case, each leg is a Hooke joint or a universal joint, a P joint and another U joint ok.

So, there are three actuators – 3 P joints and there are 2 passive U joints in each leg. It is a 3 degree of freedom robot. You can verify using the Grubler-Kutzbach criteria. This 3-UPU manipulator has very special axes geometry ok. The two intermediate R axis, what do you mean by two intermediate R axis? U is a 2 degree of freedom joint.

So, basically it has two rotary joints perpendicular to each other. So, I have one rotary joint, a second rotary joint which is perpendicular to the first one, then I have a prismatic joint, then I have another rotary joint, and the fourth rotary joint which is perpendicular to that also.

So, the two intermediate joint axis are set parallel or designed to be parallel. And the first and the last two rotary joint axis intersect at a point. So, this is called as the stationary centre of rotation. So, this is the way it has been designed ok. So, this is the picture. So, the first and the last are intersecting at a point for each of these 3 legs that is what is happening. And the second and the fourth are, this is the second and this is the fourth are they are parallel to each other for each of the legs ok.

So, in this special configuration ok, you can show that this top platform has only 3 rotational degrees of freedom ok. So, this is a spherical wrist. So, this is again in a little bit more detail, the first joint and the last rotary joint are meeting at some centre point which is the centre of rotation ok, and it is stationary.

The one, the second rotary joint and third rotary joint are parallel to each other and perpendicular to these rotary joints ok. So, this was developed by several researchers because it is the spherical wrist. So, this top mirror can now rotate about this stationary centre of rotation ok.

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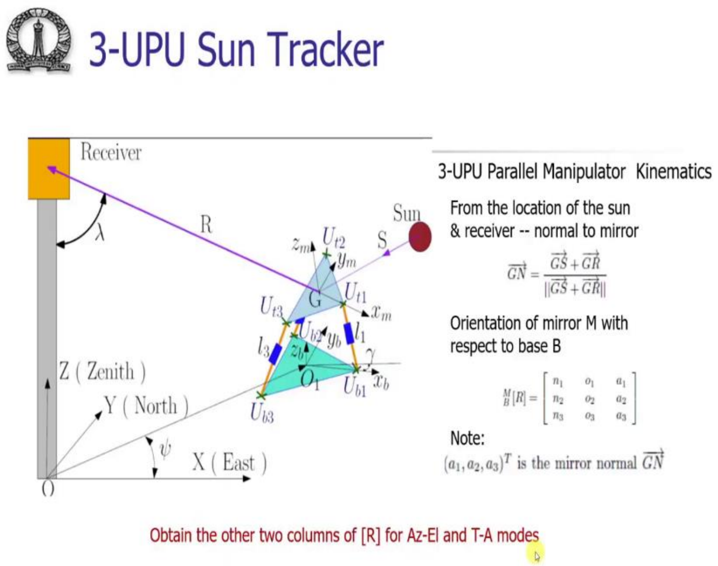

So, hence what you can derive the kinematics of this 3-UPU sun tracker? Again the basic idea is this $\overrightarrow{GN} = \frac{\overrightarrow{GS}+\overrightarrow{GR}}{||\overrightarrow{GS}+\overrightarrow{GR}||}$. The orientation of the mirror with respect to the base is given by this $\boldsymbol{n}$, $\boldsymbol{o}$ and $\boldsymbol{a}$.

And $\boldsymbol{a}$ is the mirror normal $\overrightarrow{GN}$ ok. So, we can obtain the other two columns of ${}^{M}_{B}[R]$ for azimuth elevation and T-A modes. So, what should be the $\boldsymbol{n}$ or X-axis and the Y-axis? That depends on the azimuth elevation or the T-A or the target align mode the two standard configurations which I had discussed right in the beginning ok.

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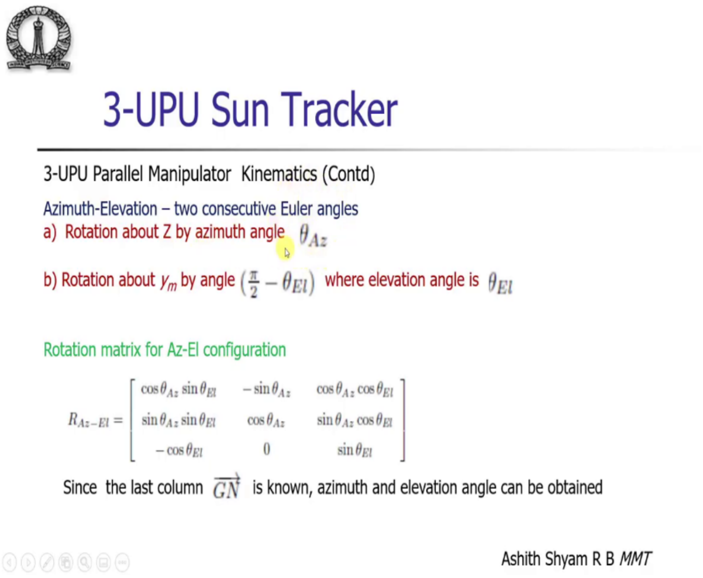

So, in the azimuth elevation configuration, we have two consecutive Euler angles. The first one is rotation about Z by this θ_{Az}, and then rotation about y by $(\pi/2 - \theta_{El})$. And the rotation matrix resulting from these two is given by this $[R]_{Az-El}$. So, you have $\cos\theta_{Az}$, $\sin\theta_{El}$, 0, and some $\sin\theta_{El}$, and so on.

The last column is the mirror normal which we know ok. We know where the receiver is, we know where the sun is, and hence we know what would be the mirror normal. So, hence comparing the mirror normal with this last column, we can find the elevation angle and we can find the azimuth angle ok.

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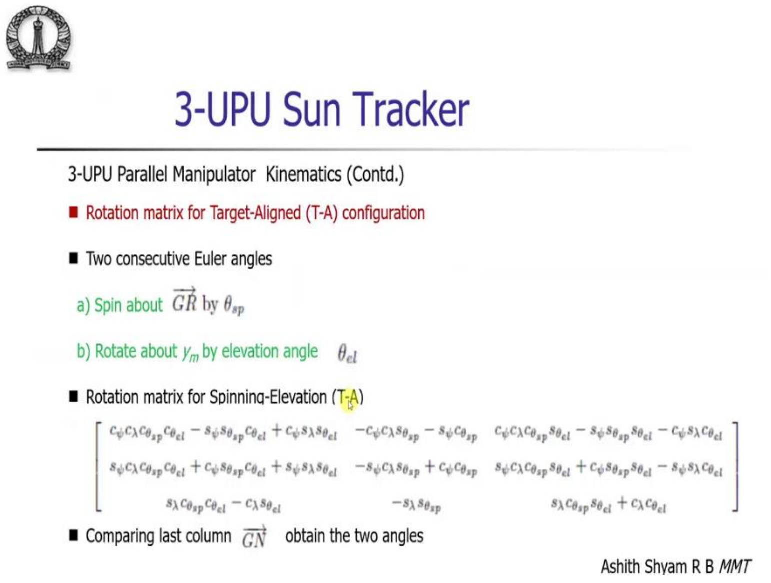

In the target aligned case, we have two rotations again. So, one rotation is spin about G to R centre of the to the receiver. As I said it is always pointed towards the receiver and the rotation about y_m by an elevation angle θ_{el}. So, the rotation matrix obtained by these two consecutive Euler angles is this horribly complicated rotation matrix.

Nevertheless, basically what you can see is there is some c_ψ, c_λ, $c_{\theta_{sp}}$, and you know spherical various things are there. The last column is the mirror normal ok. So, comparing the last column with these expressions, again we can find this θ_{sp} ok which is the spinning angle and the elevation angleθ_{el}. If you are you can go and see the actual paper if you want the real detailed steps.

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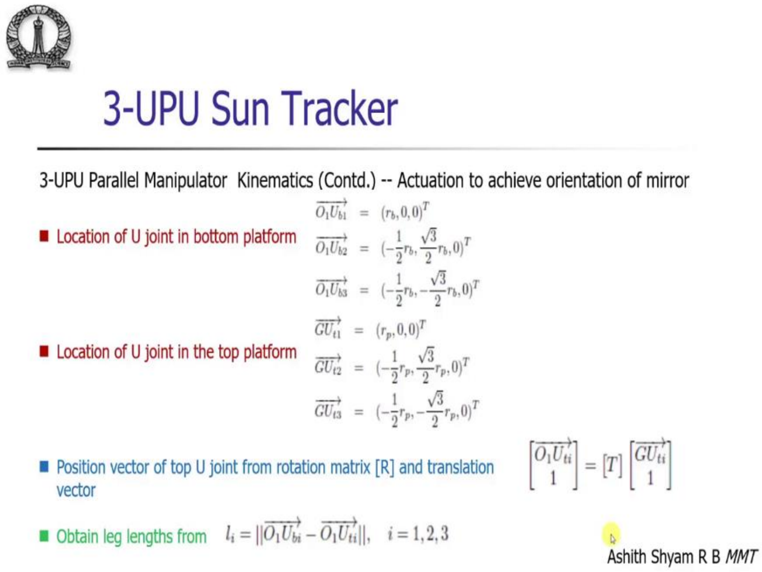

Nevertheless, we can find basically the rotation matrix either in the target align mode or in the azimuth elevation mode. So, once you know the orientation of the top platform, we can find the location of the U joint in the top platform. And the location of the U joint in the bottom platform is obviously, known in terms of the radius vector.

So, we assume that these 3 points at the bottom platform 3 U joints lie on an equilateral triangle ok with the radius of r_b from the centre to one of the corners of the equilateral triangle. So, hence $\overrightarrow{O_1U_{b1}} = (r_b, 0{,}0)^T$; $\overrightarrow{O_1U_{b2}} = \left(-\frac{1}{2}r_b, \frac{\sqrt{3}}{2}r_b, 0\right)^T$, and so on. Likewise, the top Hooke joint or the universal joint is located at r_p. We assume that the top triangle is inscribed in a radius of circle r_p– equilateral triangle.

And again we can find this $\overrightarrow{GU_{t1}}$, $\overrightarrow{GU_{t2}}$, $\overrightarrow{GU_{t3}}$ from the centre of the top platform. The position vector of the top platform thus in of each of these Hooke joint can be obtained by a transformation matrix ok. So, $[T]\begin{bmatrix} \overrightarrow{GU_{ti}} \\ 1 \end{bmatrix}$ with sum 1 added because it is a 4×4 homogeneous transformation matrix, we can find this out.

And what is does this $[T]$ contain? This $[T]$ contains basically the orientation of the top platform, and the location of the centre of the top platform which we know ok. The centre of the top platform about which it is rotating is fixed. And orientation can be obtained from finding the θ_{sp} and the θ_{el}.

Once we know the location of the Hooke joints in the top platform, we can find the leg lengths ok, l_i is nothing but the vector to the top platform, vector to the base and the magnitude of the difference of those two vectors ok.

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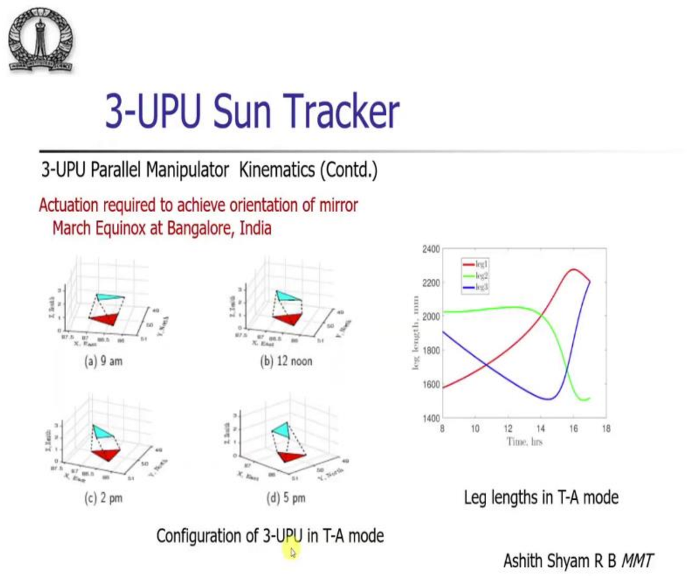

So, we can compute this leg length and then we can find what is the actuation required to achieve orientation of a mirror at the March Equinox at Bangalore ok. So, at 9 am, it looks like this; 12 noon, it looks like this; 2 pm, it looks like this; 5 pm, it looks like this. At any other time, we can find what the 3-UPU robot looks like ok, and we can compute the leg lengths. So, l_1 is this red; blue is leg 3, and green is leg 2.

So, what this plot is telling you is that if I change the leg lengths from let us say 8 am to 6 pm in the evening in this manner, the mirrors will orient in a way such that the reflected beam is always at the receiver ok.

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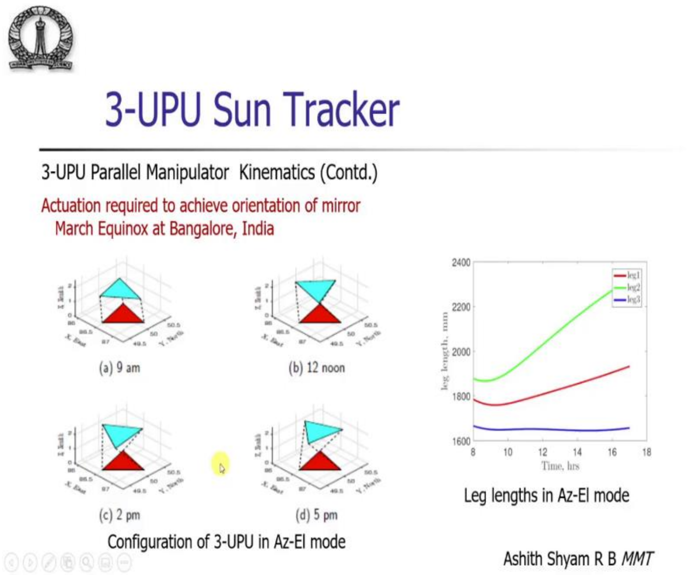

So, this was the configuration of 3-UPU in the target align mode ok, when we operate this 3-UPU devise in the target align mode. We can also compute the leg lengths in the azimuth elevation mode on the same day ok, again on the March Equinox. So, what you can see is this leg length change differently ok. So, again remember we have 3 degrees of freedom l_1, l_2, l_3. However, we need only two of them.

So, this is a redundant device, and we can use it in whatever way we want. So, we can use this redundancy in a suitable way. So, first we configured it to be in the target align mode, and then we configured it in the azimuth elevation mode ok. So, two different ways of successive Euler angles ok.

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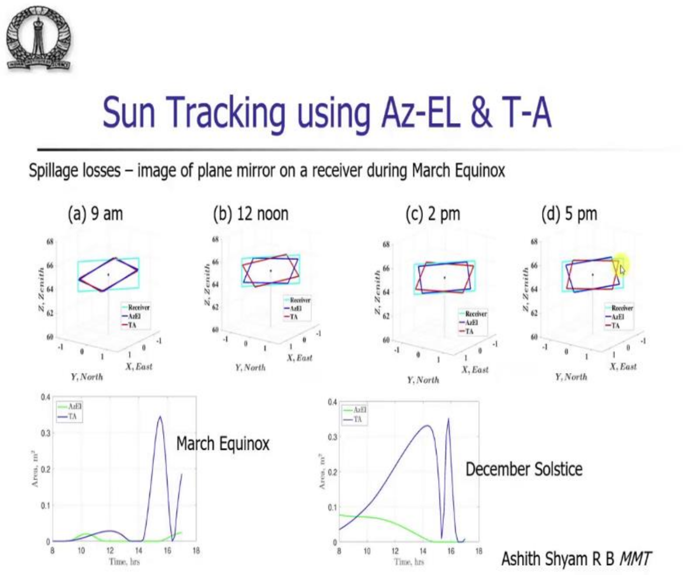

So, why do we do all this? So, one of the main important reason is that the sun tracking using azimuth elevation and target align is different ok. And what way is it different? If you see the image which is on the receiver using target align and using sun tracking, so this is red is target align, Az is the other one, and this blue cyan line is the receiver. So, what you can see is the image looking differently if you track it using the target align mode or if you track it using the azimuth elevation mode.

So, sometimes the image is going out of the receiver ok. And for example, you can see a small quantity here and a very small quantity here, but these small quantities are different for the two different configurations ok. So, this is the plot of this spillage, which is how much area is outside the receiver for target align which is this blue and azimuth elevation which is the cyan ok. So, as you can see the cyan one is smaller for March Equinox ok.

So, likewise at December solstice you will get a different amount of spillage ok. So, how much is this spillage? This is very small ok. So, the difference in both of them would be like maybe 3 to 5 percent, but even that is very important when you are doing sun tracking, and when you want to concentrate the energy onto the receiver.

So, what the idea is that since we can run this 3-UPU manipulator in either in the azimuth elevation or target align mode, we can switch electronically depending on the time of the day and the date of the year, where the spillage losses is less ok.

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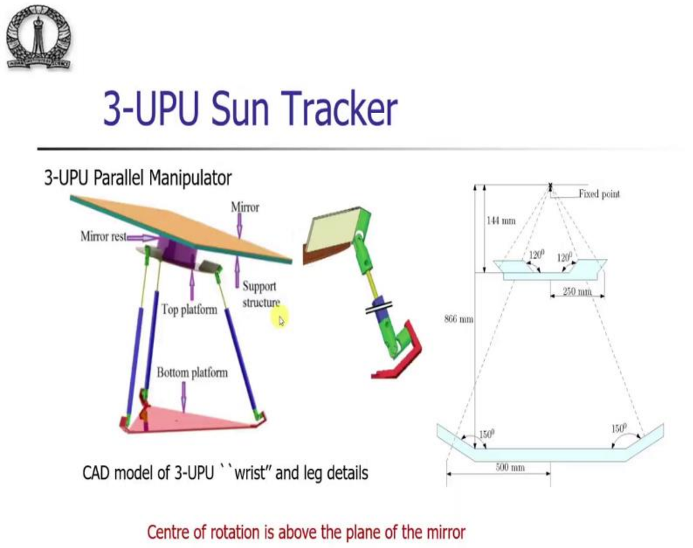

So, this is a CAD model of the 3-UPU sun tracker which was built. So, basically this is the bottom platform. This is a way we can implement these two rotary joints to be parallel and two other rotary joints to meet at a point. So, it turns out that these rotary joints meet at this fixed point which is a little bit above the plane of the mirror ok.

This is due to manufacturing and design and so on. We cannot have the fixed point on the mirror itself so easily. So, the centre of rotation is a little bit above the plane of the mirror by about 144 mm. And these distances are chosen, and this angle is 150 and so on, and this is 500 mm.

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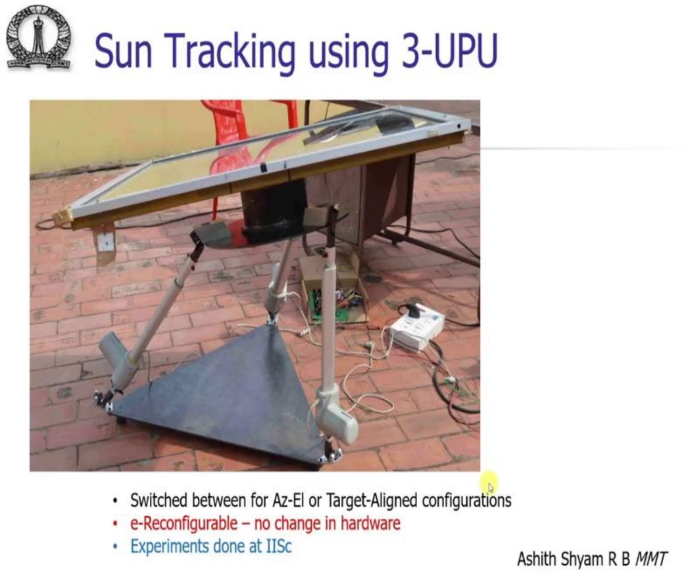

So, this was built ok. And the plan is that we are going to switch between azimuth elevation and target aligned configuration depending on when the spillage losses is less. And this is done using computer. There is no change in the hardware ok. So, this device was built. As you can see that this is the leg, this is one U-joint, this is another U-joint at the top.

And the since that point of rotation is above little bit, so we have placed the mirror a little bit above the place where the Hooke joints are ok. So, centre of this mirror is actually the centre of the rotation.

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So, we carried out some experiments. And this is the result of one experiment which shows that at 3:18 pm on May 24, 2017 ok. When the roof 3-UPU was operating in the azimuth elevation mode, the image was here ok. It took about 1 or 2 minutes for the students to run the other program which is the target aligned mode. So, at 3:20 pm the image is here.

So, as you can see it is more or less at the same place, little bit of difference is there ok, so that is also due to the error. So, these are some of the geometry. So, this is about 6.7 metres away from the centre of the mirror ok and so on. So, what this experiment is telling you is that we have a 3-UPU sun tracker which can be switched between T-A and azimuth elevation mode electronically ok. And why do we want to do that? We want to reduce spillage losses.

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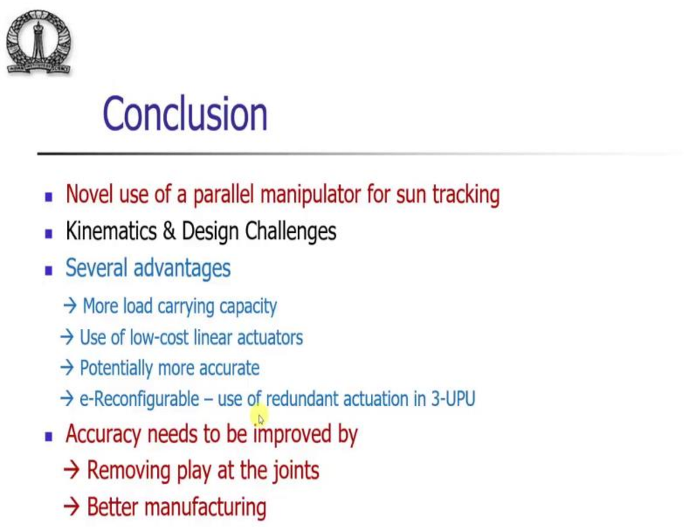

So, in conclusion, we have a novel use of a parallel manipulator for sun tracking ok, with there are several kinematics and design challenges. The motors have to rotate very very slowly with and also very accurately. There are also lots of advantages using a parallel robot. We can carry more load - basically we can carry bigger mirrors. We can use low cost linear actuators; it is also potentially more accurate because the deflections are less.

And it is e-Reconfigurable, because we can use the redundant degree of freedom in this 3-UPU to switch between target aligned, and the other one is azimuth elevation ok. So, both these sun trackers were built at IISc by students. So, there is a significant need of improving these. So, we need to basically remove the play at the joints, and we need to do better manufacturing.