Product Design and Manufacturing
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Lecture – 32
Reverse Engineering

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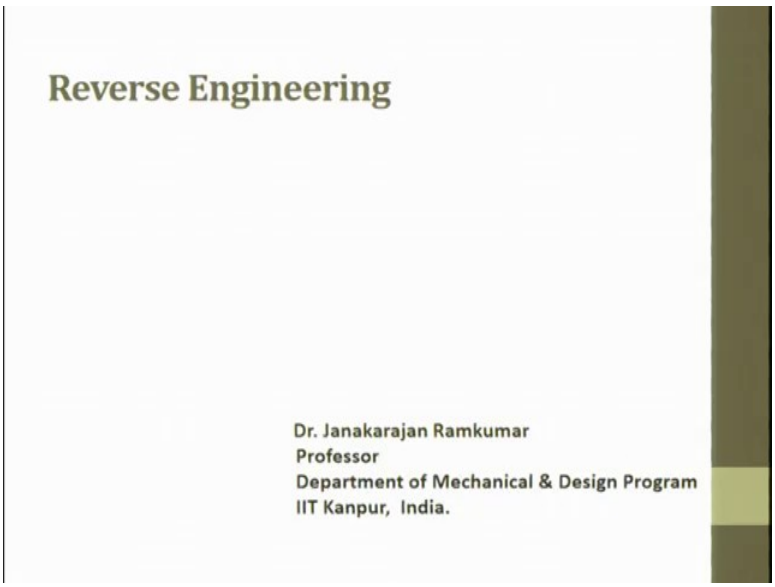

Welcome to the lecture of Reverse Engineering.

The topic itself is very interesting, you are trying to do engineering in a reverse fashion. what does it mean? in engineering terms we start from a point and go to a line then go to an edge and then to a surface to develop a product. In reverse engineering, you have a product and you go back to the final destination of getting a point. In today's world, there is lot of discussion going on whether it is legal whether it is good or bad, but reverse engineering is has become an essential thing to be followed.

If you want to understand the state of the art of a product, for a process, for a design then you have to do reverse engineering and when you do reverse engineering it should be used for professional growth. Once you do reverse engineering of the product, you will find what are all the flaws in the product? you would look for improvisation from the standard part whatever was available to you. For example, in QFD, Quality Function

Deployment, what we do is we try to see the state of the art by looking at several state of the arts and then we try to fix our specification and move towards our specification.

Reverse engineering is part and parcel of product development, if you do not do reverse engineering you will not understand where are you placed amongst your competitors.

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The content in this lecture is going to be reverse engineering, its definition, importance, applications, processes and 3D scanning, hardware and its introduction and reverse engineering hardware which is of contact, not contact and destructive type.

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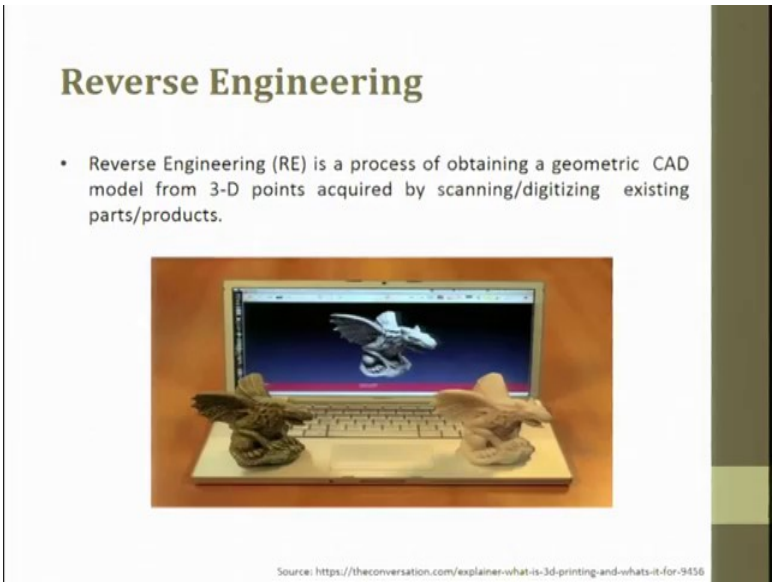

What is definition for reverse engineering? the reverse engineering is a process of obtaining a geometric CAD model from 3D points, acquired by scanning/digitizing existing parts/product. For example You look at a product and try to take a photo of the product or you try to replace that image/photo which was taken through the light now through a laser.

You try to get points of data also called as a point cloud of data and from that you try to reconstruct a CAD model and this CAD model can be used for analysis and further development, the process of obtaining a geometric CAD model from 3D points acquired by scanning/digitizing of an existing part.

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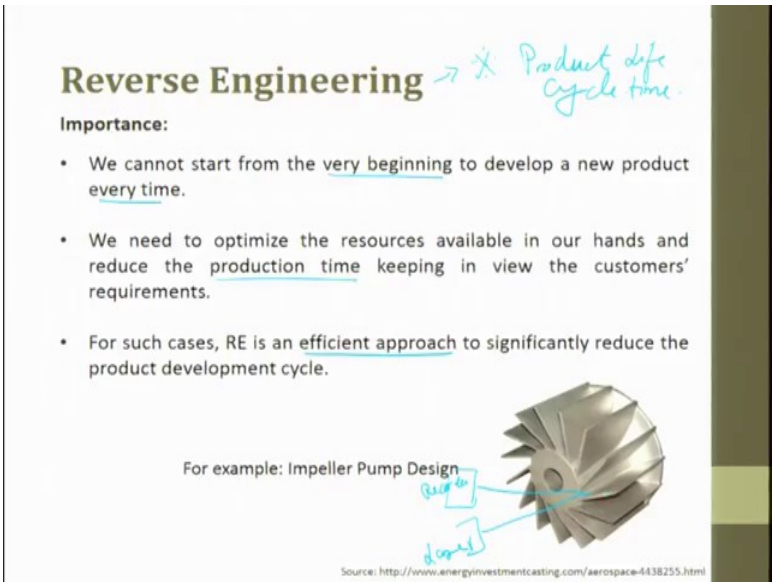

Why is it important? Because we cannot start from a very beginning to develop a new product every time that means, to say we cannot re-invent the wheel, whatever is already existing pull it up and start developing on top of that towards your customization of your problem for a customer. So, every time we can't start from new either we use what is available within our reach or a technology or we try to see what other products are available, understand the technology and try to take that into our product and develop it. We need to optimize the resource available in our hands and reduce the production time.

This is very important aspect, reverse engineering plays an important role in reducing the product life cycle time. So, keeping in view of the customers requirement in such cases reverse engineering is an efficient approach to significantly reduce the product development cycle, it is not ethical to just copy and paste the products, What you do is you try to get the data and try to improvise the data towards your customer's requirement by applying customization. Like in design of impeller people try to take a reverse engineering of it

What it does is, you use a laser to hit, then tries it to reflect data. This laser have a recorder, the laser hits it reflects the record and you start getting the data in the x-y-z plane.

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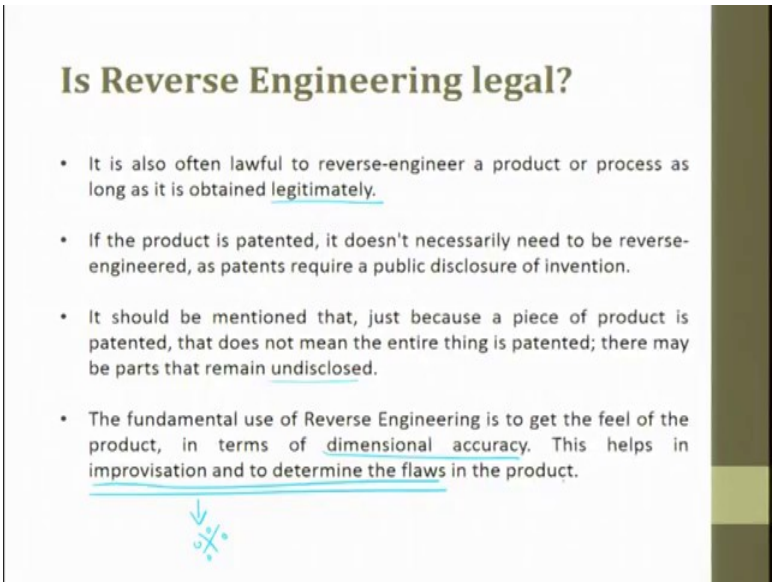

Is reverse engineering legal? It is also often lawful to reverse engineer a product or process as long as it is obtained legitimately. If the product is patented it does not necessarily need to be reverse engineered as patents require a public disclosure of invention. It should be mentioned that just because a piece of product is patented that does not mean the entire thing is patented, there maybe parts that remained undisclosed.

The fundamental use of reverse engineering is to get the feel of the product in terms of dimensional accuracy and performance, this helps in improvisation and then to determine the flaw in the product. You have a product which is excellent, but try to improvise it and try to determine what is missing in it and customize it towards your product.

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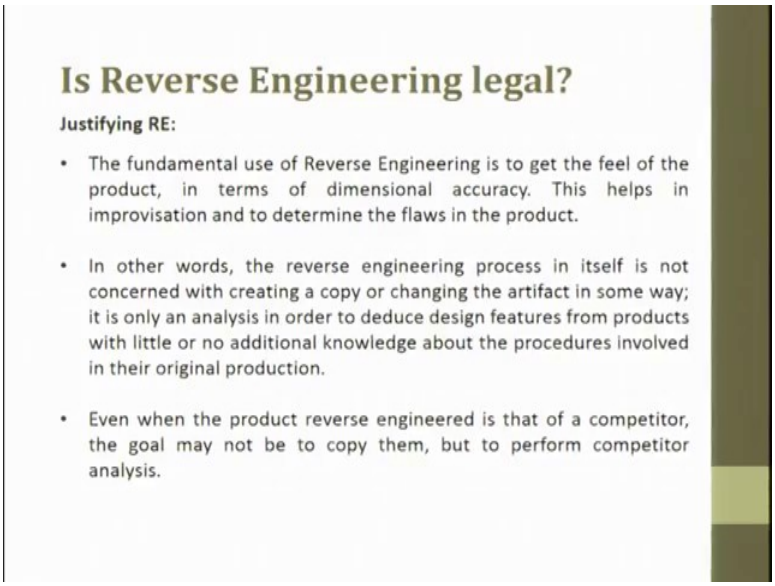

The justification of RE: the fundamental use of RE is to get the feel of the product in terms of dimensional accuracy this will help in improvising and to determine the flaws in the product.

In other words reverse engineering process is itself is not concerned with creating a copy or changing the artifact in some way, it is only an analysis in order to deduce design features from the products with little or no additional knowledge about the procedure involved in their original production. Even when the product reverse engineered is that of the competitor the goal may not be to copy them, but to perform competitor analysis.

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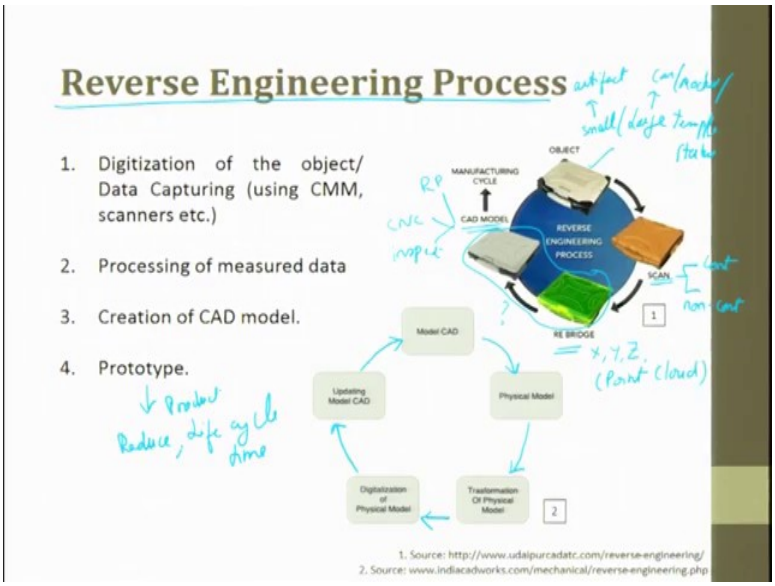

What are are all the processes which are involved in reverse engineering? So, reverse engineering processes; first what you have is you have an object, this objects can be small, it can be large for example, it can be an artifact, car, rocket, temple, a statue. It can be as big as a car, rocket, temple, mosques, statues whatever it is.

The object can be small, the object can be large. We take that object then we try to scan the object, during scanning we try to take the data points.

Then we try to section the object into several planes and in each section we would try to look for x-y-z data in that plane. So, once I get that x-y-z data in one plane then I can start using it for reconstructing. So, scanning is something which is the next major step the scanning can be done by two ways it can be done by contact methods, it can be done by non-contact methods, contact methods means I can touch and try to record the data in the x, y, z plane. Second thing is I need not touch, I use a laser reflection of the object from there I try to take data points. hence scanning can be done contact it can be done non-contact.

Then we try to take all the data of x, y, z point in 3D and from this you can also try to get a plane data, it will try to collect all the data. So, it is called as point cloud data, it collects all the point cloud data and then it tries to bridge whatever data we get here, it need not and it will not be perfect. So, you have to use several algorithms to remove the imperfections in the point cloud data, that is basically signal to noise ratio, you apply

some filters remove, those noises and then you try to work on particular patches and when you try to work on this particular patch. You can remove it and then you can try to reconstruct a CAD model.

From a CAD model, moment a CAD model is created you can try to go for CNC machine, you can go for inspection, you can also go for rapid prototyping. So, the CAD gives you lead in manufacturing. If you look at it, it is a physical model, a transformation of a physical model then you try to digitize the physical model, then you develop a CAD, update a model of CAD then you develop a model and then this is brought back to the physical model.

It is a cycle which goes around,

Digitizing of an object: that means, to say data capturing is a very important step and this scanning of data and digitizing, scanning and then bridging of the data is very important and lot of mathematics is involved and interestingly if you see today you have many mobile phones which has two cameras.

The logic for these two cameras is to get the depth information more clearly as in a plane. The difference in time is used here for trying to get more realistic data, the scanning technique and the scanning accuracy dictates the next process of point cloud data and from the point cloud data, you try to develop a CAD data, this portion of converting point cloud into CAD data even today a most sought after area, there are few experts only who can work on this area of converting this point cloud data into a CAD data because it needs lot of expertise. The second thing is processing of measured data, then creation of CAD model then at last is prototyping.

Why do you want to do prototyping? You want to reduce product life cycle time.

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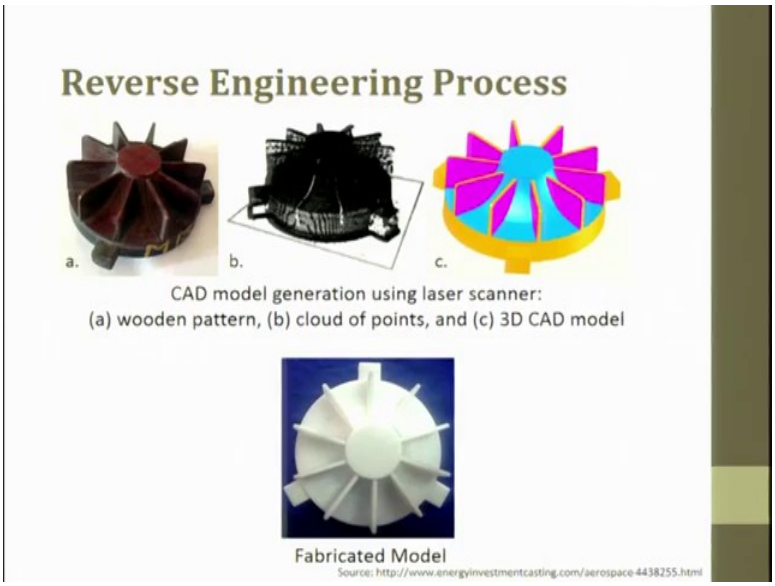

In the figure there is a wooden pattern which is made and we do the scanning, it can be contact or non-contact and when you get a point cloud of data then you see that there is lot of error in the point cloud of data, and then these errors are removed and what you get is a 3D data. You can directly send it to a CNC machine or you can directly send it to a RP machine so that you try to get the same product manufactured. Depending upon the time and the accuracy you spend here, the output will be very close to the input whatever it is.

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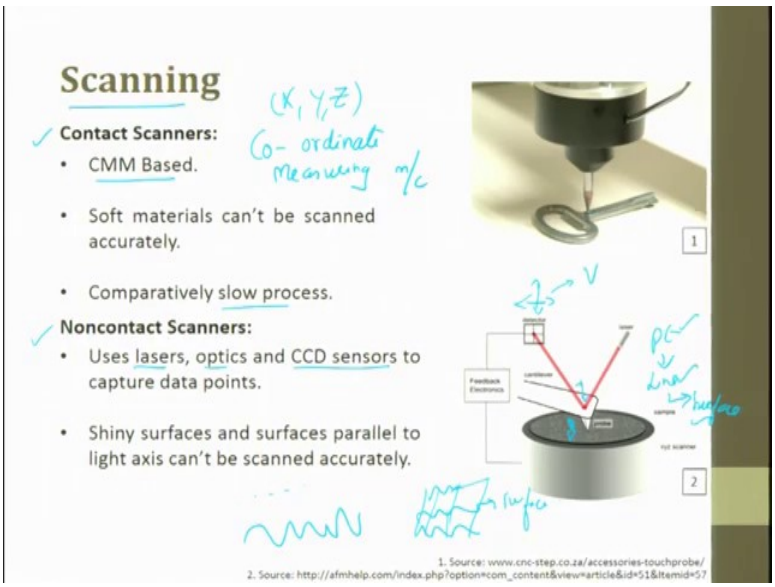

There are two types of scanning, one is called as contact type the other one is called as non-contact type, in contact type we always use a Coordinate Measuring Machine. This coordinate measuring machine is very slow in nature and if you have a very soft material something like a latex, rubber, tissue. All these things when you touch, they are elastically deformed hence the data you get from them may not be correct, do not go varyingly and the error will be submicron errors are it is not in millimeters.

In coordinate measuring machine, we touch its probe on the workpiece and we get coordinate points x, y and z points. So, that's why it is called a coordinate measuring machine, in non-contact type we can use laser or optics and CCD sensor to capture the data. This is a typical atomic force microscope working principle image.

There is a probe, at the back side of the probe you put a reflecting material. So, the laser hits at the back side of the probe. The moment probe moves up and down, this laser also goes up and down and this is directed by a photodiode, this photodiode tries to move in left and right direction and it will try to give the voltage.

Feedback electronics is used to improve the voltage into linear displacement So, again here what you can get is a point data. From a point you convert it to a line and several of these lines convert together to make a surface, to say with this technique you can get 1D, 2D and 3D. This is a surface data, shiny surfaces and surface parallel to the light axis cannot be scanned accurately ,this is the limitation of this process however, this can be overcome by several techniques

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In a 3D scanning process, for an ideal 3D scanning process the scanning procedure has been divided into acquisition of data, alignment of data, mesh generation, post processing and simplification. These are the five steps which are involved in 3D scanning process. Suppose if it is not aligned in one particular plane, it is misaligned. So, alignment can be a problem.

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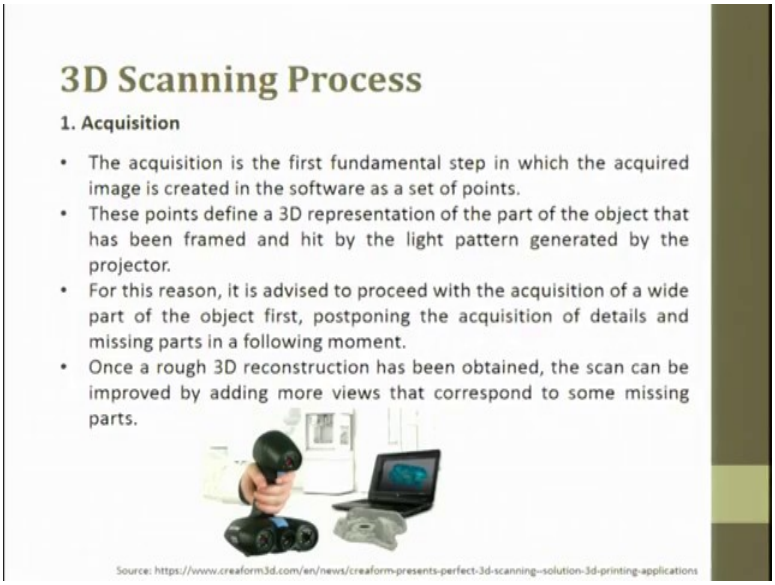

Acquisition: acquisition is the first fundamental step in which the acquired image is created in the software as a set of points. These points define a 3D representation of the

part of the body that has been framed and hit by the light pattern generated by the projection. For this reason it is advised to proceed with the acquisition of your wide part of the object first, postponing the acquisition of deatails and missing parts in a following moment. Once a rough 3D construction has been obtained, the scanning can be improvised by adding more views that corresponds to some missing part.

For example, we can make a 3D image of an object by looking at it from different viewing angles or directions.

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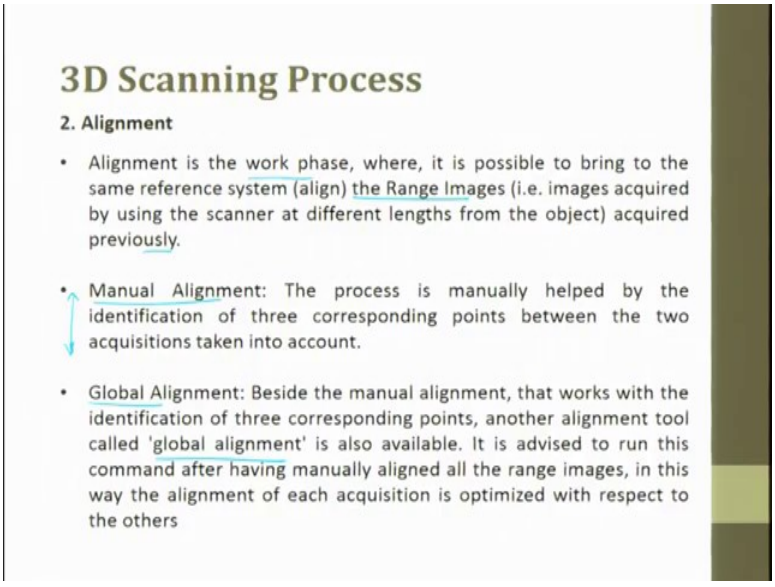

Alignment: alignment is a work phase where it is possible to bring to the same reference system, the range images (acquired previously), for example if I have an object placed in a plane and suppose if the object is slightly deviated then there would be an error.

Whatever data you acquire and then you try to project it on the plane, the plane will have some error, it is always better to remove this error in the plane in the first position and then start acquiring data or you try to calibrate your camera first, understand the error in the camera and then start working on the image. Alignment is the work phase where it is possible to bring to the same reference system, the range image acquired previously, the alignment can be done manual, the alignment can be done global. So, the process is manually helped by the identification of three corresponding points between the two acquisition taken into account.

There is manual alignment and global alignment, manual alignment that work with the identification of three corresponding points another alignment tool called as global alignment is also available, it is advised to run this command after having manual alignment of all the range images, this way the alignment of each acquisition is optimized with respect to each other.

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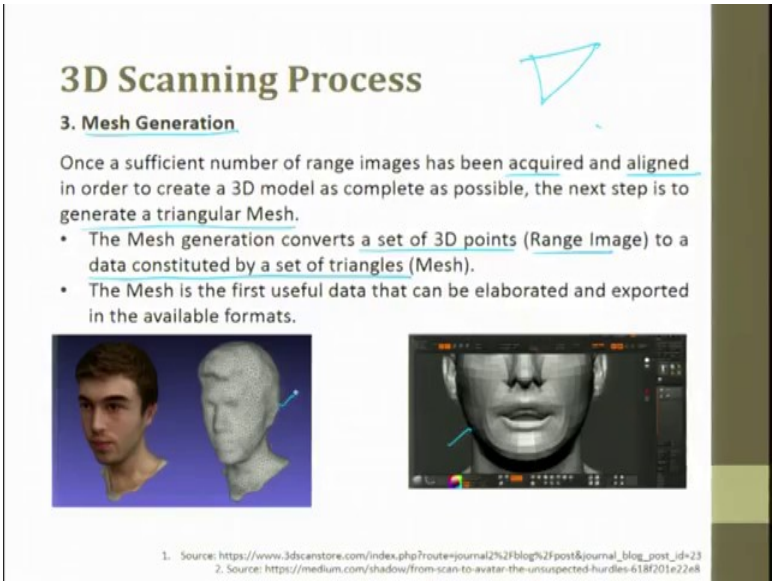

Once you made the point data, the point data is assembled and you try to do a mesh generation, once a sufficient number of range images have been acquired and aligned, in order to create a 3D model as a complete as possible the next step is to triangulate the mesh.

The mesh generation converts a set of 3D points, a range image to a data constituted by a set of triangles. Earlier you had data points, now these data points are connected into mesh, into triangles, the mesh is the first useful data that can be elaborated and the exported in the available format. The point cloud data is converted into a mesh data, then this mesh data is exported for other use.

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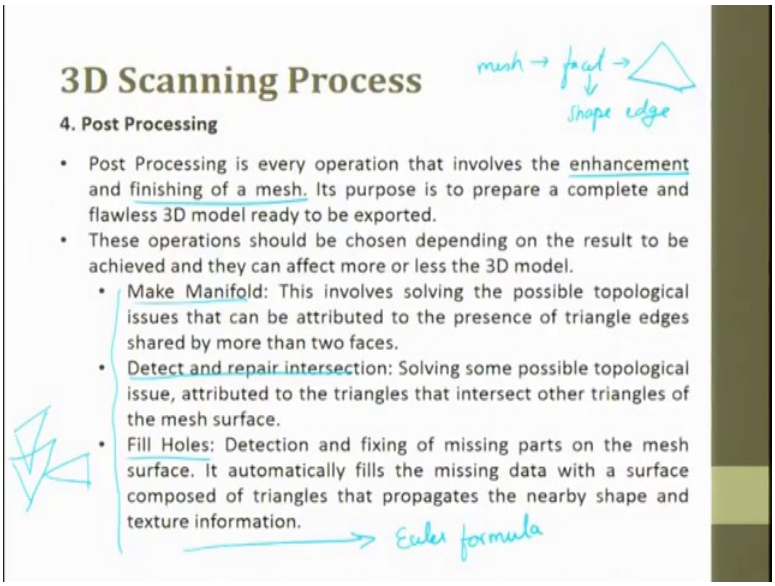

Then comes the post processing: post processing is every population that involves the enhancement and finishing of the mesh.

So, the mesh whatever you do are nothing but facets, these facets are always having sharp edges, sharp edges. So, in order to remove the sharp edges and make it smooth; so we always try to enhance and finish the mesh, it is possible to prepare a complete and a flawless 3D model ready for export, these operations should be chosen depending on the results to be acquired and that can affect more or less a 3D model. Make manifolds: this involves solving the possible topological issues that can be attributed to the presence of a triangle edge shared by more than two facets is called manifolds.

Deduction and prepare: so, what happens is deduction means you might have a triangle, you might have another triangle like this or you might have a triangle like this which pierces into the other triangle. So, now, these things are called as defects and repair. So, you detect the defects and then you repair the intersection, solving some possible topological issues attribute to the triangles that intersect other triangles of a mesh surface. Fill holes: detection and all these things, if you start working on CAD, if you read through course you will see that there is something called as Euler's formula. So, in Euler's formula what it does is it checks for overhanging, it checks for number of holes and then it tries to validate an object.

Post processing is trying to validate the object, the meshes can be hanging here and there, but if it has to be completed and form a solid then you have to do all these things, detection and fixing of missing parts on the mesh surface, filling holes. It automatically fills the missing data with a surface correspondence to the triangle that propagates the nearby shape and the texture information.

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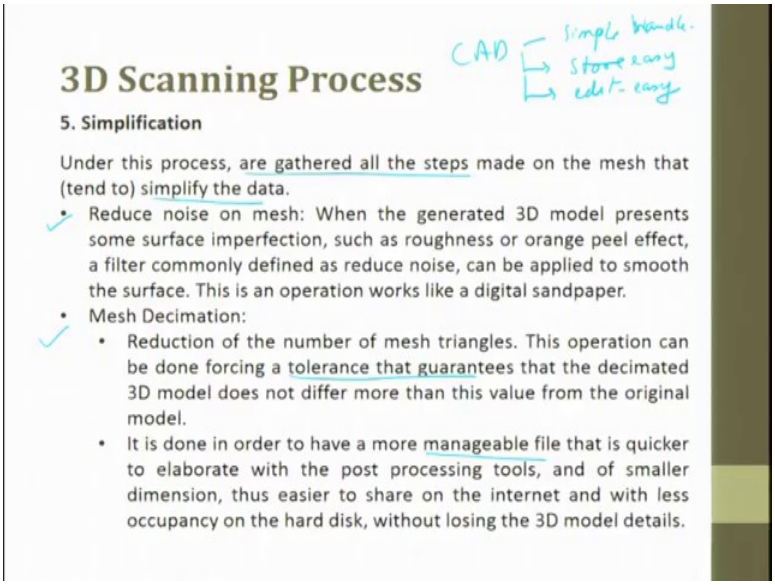

The last thing is simplification: under this process, are gathered all steps made on the mesh that tends to simplify the data.

- Reduction of the noise and Mesh decimation.

Reduction of a number of mesh triangles because each mesh is going to operate, it is going to eat away a lot of space. So, maintaining so much of meshes means it is going to have a huge set of data in the server. Storing and editing becomes a problem, in order to generalize and reduce the number of data points, this operation can be done forcing a tolerance that guarantee that the decimated 3D model does not differ more than the value for a original model, it is done in order to have a more manageable file.

When we talk about CAD, we talk about three things, one is simplicity that how easier it is to store and how easy to edit. The simplification is more towards that simple to store, simple to handle, easy to store, and easy to edit, simple to handle means, it does not occupy a huge space.

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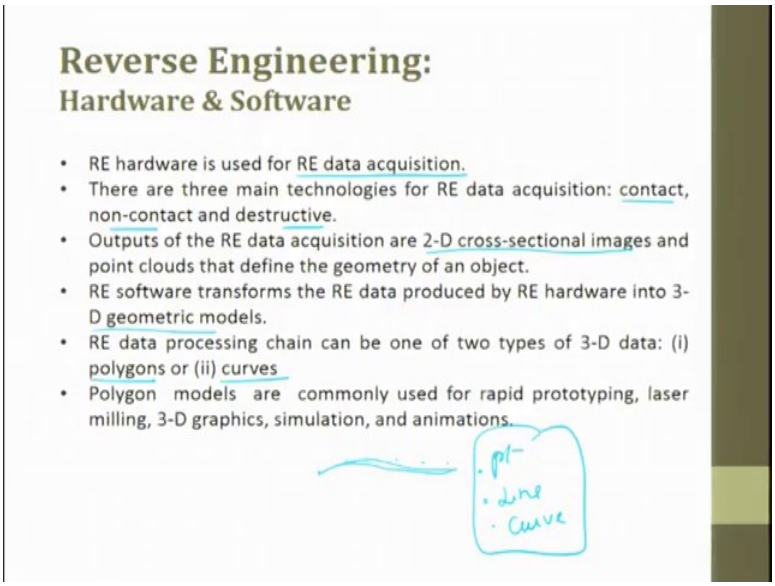

Reverse engineering hardware and software: when we talk about reverse engineering hardware and software, RE hardware is used for the RE data acquisition. There are three major technologies for RE data acquisition one is

- Contact.
- Non-contact.
- Destructive.

Generally we do not prefer destructive because it is very costly affair. We may damage or we can lose the part, output of the RE data acquired are 2D cross sectional image and point cloud that defines the geometry of a object.

RE software transforms the RE data produced by RE hardware into a 3D geometry, the RE data processed chain can be one of the two types of 3D data, it can be a polygon data or it can be curves. If you have points and if you want to connect the points through a line and if you can define a line point, if you know to define a point, if you know to define a line, if you know to define a curve, then rest all is a piece meal of whatever you have. Polygon models are commonly used in rapid prototyping, laser milling, 3D graphing, simulation and animation.

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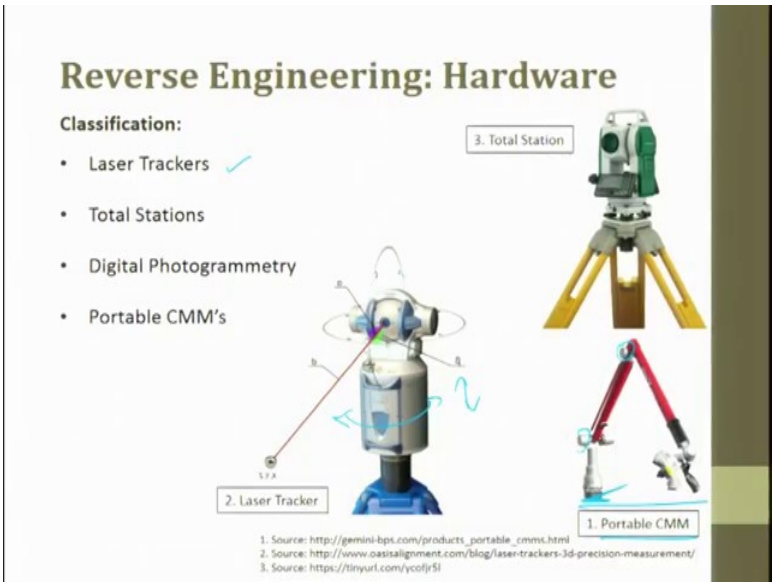

When we talk about hardware, there are four different types of hardwares. one is called as the laser tracer in this system where and which it can swing around this plane and this can swing around this and the height can be adjusted. The next one is a total station.

it is basically used by civil engineers to check the to check the distance, next is digital photogrammetry. It is taking a digital image and then converting a digital image to get data and the last one is a portable CMM.

In this portable CMM, it is interesting to know that all the data references are given with respect to this plane and if this plane is not aligned then all the data you get in x, y, z plane is that data with a small error. That's's why the alignment is very important, portable CMM is another thing, where in which you can take the CMM go to any place, put it in any surface make that surface as a flat and then you try to calibrate your CMM data points and then you start measuring. The encoders over there try to take all the error, calibrate it and then start taking measurements.

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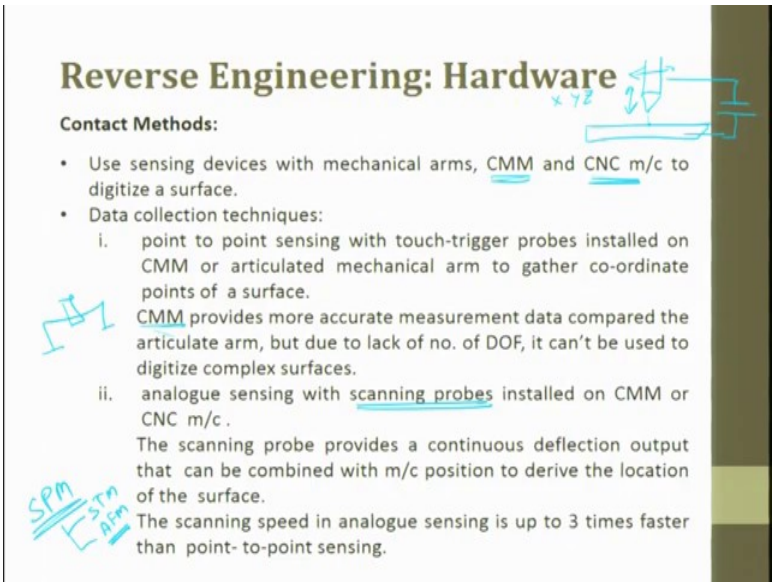

contact type used sensing devices with mechanical arm, CMM and CNC machine to digitize a surface.

Even a CNC machine can be used to digitize a surface very easily. For example a steel or a metal then you have a workpiece as metal. You try to make a connection between these two, and when it comes closer it touches, the resistance goes to infinity and from there you can start noting down the x, y, z data points, this fellow can move step by step and it can move in x, y, z plane hence a CNC machine can be used as a coordinate measuring machine. The point to point sensing with touch trigger probe installed on a CMM or an articulated mechanical arm.

The CMM provides the more accurate data, measured data compared to articulated arm, because CMM has a frame where in which the frame is standard, articulated arm is also there. So, the reference plane is a challenge, but due to lack of number of degrees it cannot be used for digitizing complex surfaces. Analogous sensing with scanning probe installed on CMM or CNC machine.

Scanning probes: the scanning probe provides a continuous deflection output that can be combined with a machine position to derive the location of the surface. Scanning probe means a probe without touching keeps scribing on the surface, the scanning tunneling microscope, scanning probe are called as SPMs. In this comes your scanning tunneling microscope, atomic force microscope, when you talk about in nanoscale and

microscale, if you want to measure the features, contact measurements is not possible that means if the diameter is too large, lasers are not possible, light is not possible. So, there we use contact with scanning probe microscopes.

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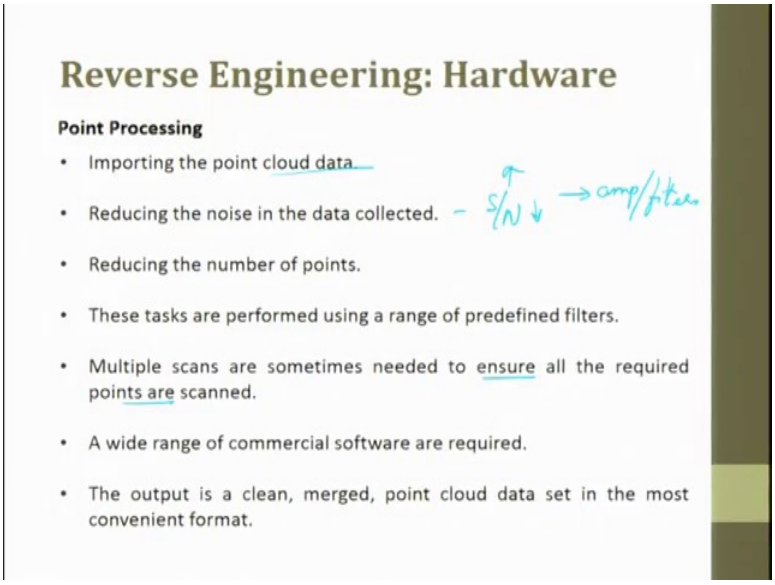

Point processing: importing the point cloud data, reducing the noise of the data, you have to reduce the noise and increase the signal. You have amplifiers, you have electronic filters. Reduce the number of points, these tasks are performed using a range of predefined filters, multiple scans are sometimes needed to ensure all the acquired points are scanned. So, you scribe it two three times to make sure all the data points are got .A wide range of commercial softwares are available today, the output is clean merged point cloud data set is the most convenient format.

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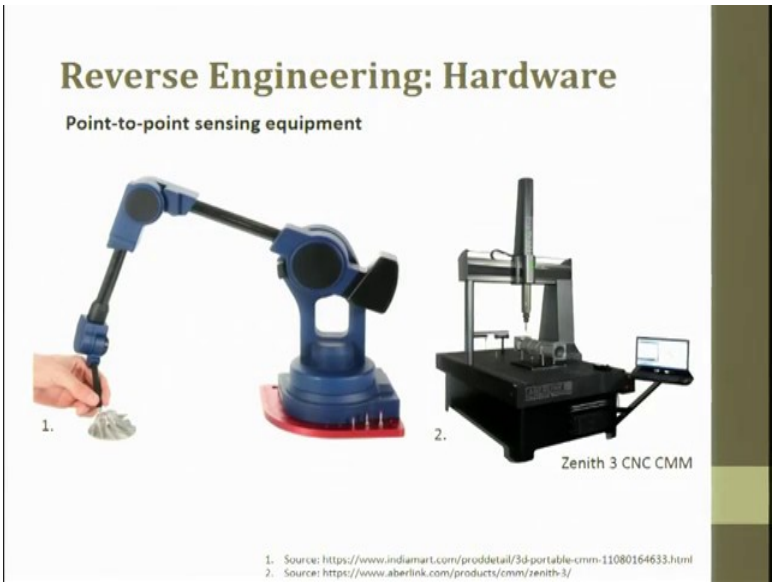

This is a point to point(P2P) sensing system, this is CNC-CMM system, the probe touches and is not electrified. It is only a physical touch you try to measure and it is a trigger probe the other one is also the same, it (P2P) has a frame in which the arm is used, here(in CNC/CMM) arm is not used, a gantry is used. So, the geometry is different the structure is different, but the data whatever you get is a point data.

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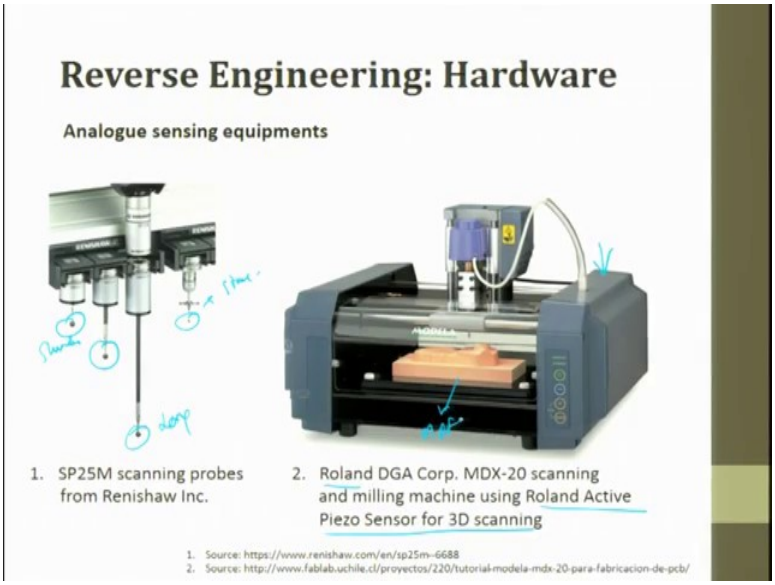

There are different types of probes, a star probe, long lengthy probe, a slender probe.

These are all probes which are attached to the CMM and you get the data. here is Roland which is a machine where in which it is used to scan and then mill . for example, you can put a surface which you want to scan, it scans the surface and then it executes the milling operation in a single machine. So, scanning and milling machine used Roland active piezo sensor for 3D scanning. Scanning can happen here and then the data is taken to it and then data is executed, this is nothing but an mdf, which is a which is a wood based material.

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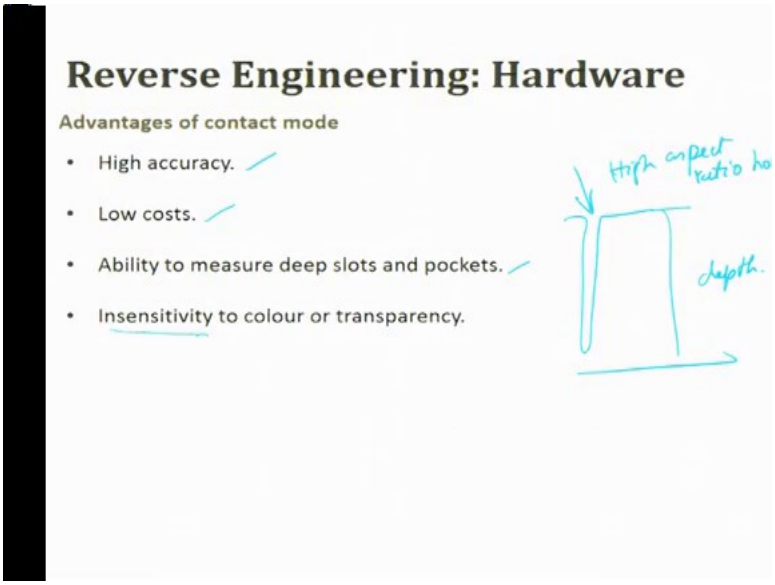

The accuracy of contact measurement, is highly accurate, it is low cost, ability to measure deep slots -you wanted to do high aspect ratio holes then contact measurement is the only way, insensitivity to colour or transparency is removed from here.

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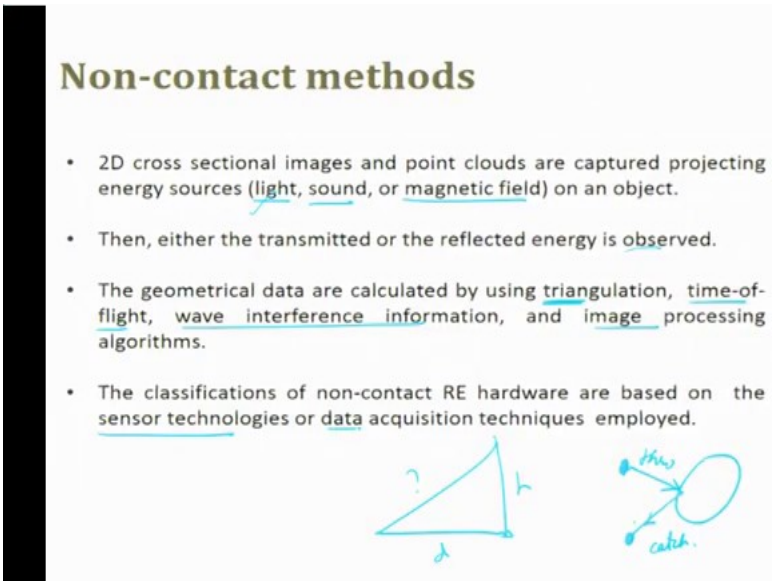

The next one is non-contact type method, here we use a 2D cross section image or a point cloud are captured, projecting an energy source like light, sound or magnetic field.

But predominantly what we working on is using light, but there are acoustic based sensors which are available for measuring the surface. Some magnetic field on the object, then either the transmitted or the reflected image is absorbed and the geometric data is calculated by triangulation method, height is known, distance is known.

this is triangulation method next is time of flight where you have an object the X-ray is thrown from here the X-ray is collected here. So, this is throw and catch.

wave interference interferometer, here we try to create an interference pattern and we try that pattern to strike the surface and the reflection is taken and countered and several other image processing algorithms are used. The classification of non-contact RE hardware are based on the sensor technology or data acquisition technology.

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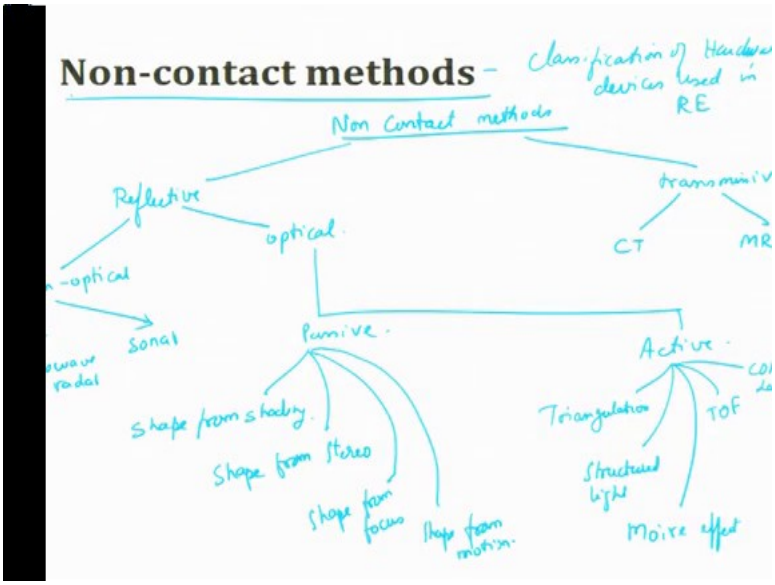

Non-contact methods: can be on reflective or it can be on transmitive. CT and MRI are also non-contact techniques in which we try to get the data, in reflective type again you can have non optical or optical.

- In non-optical, you can have microwave, microwave radar which is used in defense application, you can also use sonar which is used in the ships.
- In the optical way you can have two classifications, one is called as active, the other one is called as passive

In passive you can have shape from shading, then you can have shape from stereo, you can have shape from focus, you can have shape from motion. When we talk about active we can talk about triangulation ,we talk about structured light, we talk about Moire effect we can have time of flight and we can have laser, coherent laser.

These are the classifications of hardware devices used in RE, this tries to talk about the complete gamut of things which are available.

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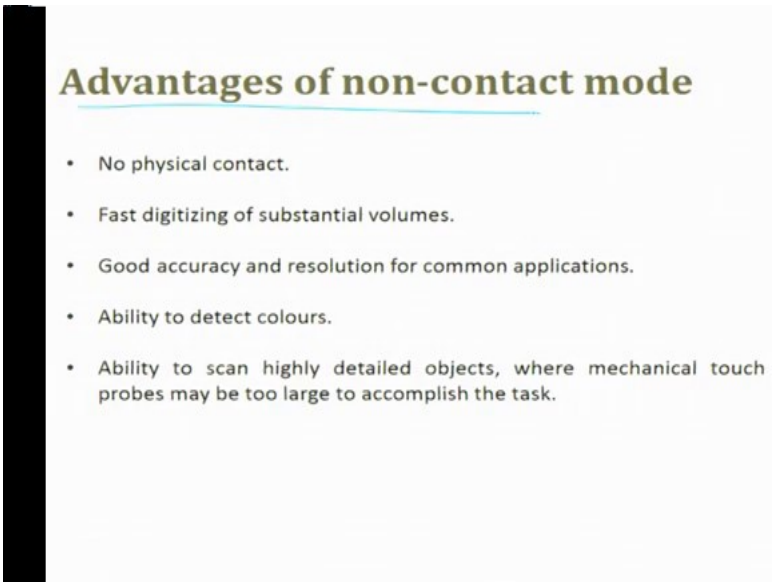

What is the advantage of non-contact type?, no physical contact, fast digitization of sustainable volume, good accuracy and resolution for common applications, ability to detect colour can be done, ability to scan highly detailed objects where mechanical touch is not possible, all these places we go for non-contact type coordinate measuring machine or non-contact techniques.

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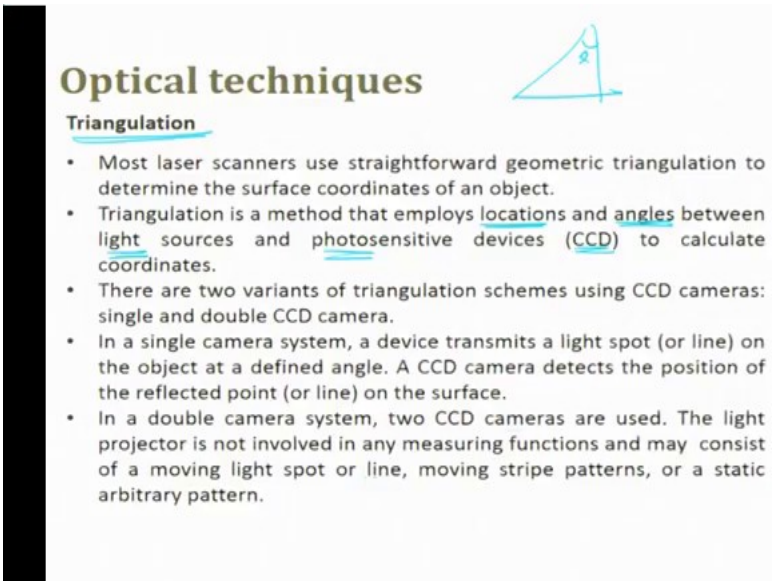

The technique which is used in optical, most common is triangulation, most laser scanners use first straightforward geometric triangulation to determine the surface coordinates of an object.

Triangulation is a method that employs location and angle between the light source and the photosensitive device that is nothing, but a CCD to calculate coordinates. There are two variants of triangulation schemes using CCM that is charge coupled device cameras, single and double CCD cameras in single camera system a device transmits a light spot on to the object at a defined angle. A CCD camera detects the position of the reflected point on the surface.

In a double camera system, two CCD cameras are used, latest mobile phones use the light projector is not involved in any measurement function and may consist of a moving light source or line, moving strip patterns or static patterns.

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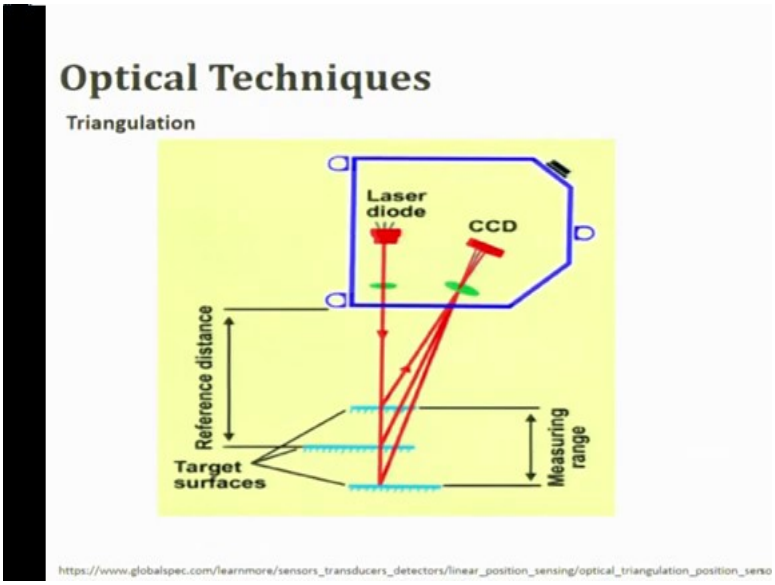

This is triangulation, you can see laser coming out of this, trying to hit the object and then it tries to reflect back and here is a charge coupled device which is nothing, but a CCD camera. So, this is the range with which the object moves and this is the reference distance and these are the target surfaces, this is a laser, this is an object or this is a device inside which a laser diode is there and a CCD is there.

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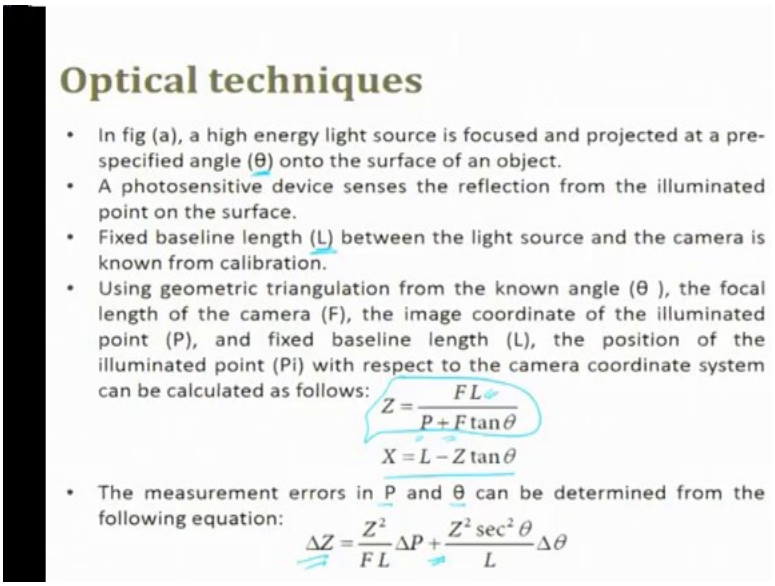

So, from figure a the high energy light source is focused on and projected at a pre specified angle θ onto the surface, the photo device senses the reflection from the illumination point of surface, the fixed base length is L. Finally, if you look at it you get through the formula of this where is at the geometric triangulation from the known angle θ the focal length of the camera is F. the image coordination of the illuminated point is P, the fixed length is L, the illustration point Pi with respect to the camera coordinates coordinate system is given:

$$Z = \frac{FL}{P + F\ tan\theta}$$

$$X = L - Z\ tan\theta$$

$$\Delta Z = \frac{Z^2}{FL}\Delta P + \frac{Z^2\sec^2\theta}{L}\Delta\theta$$

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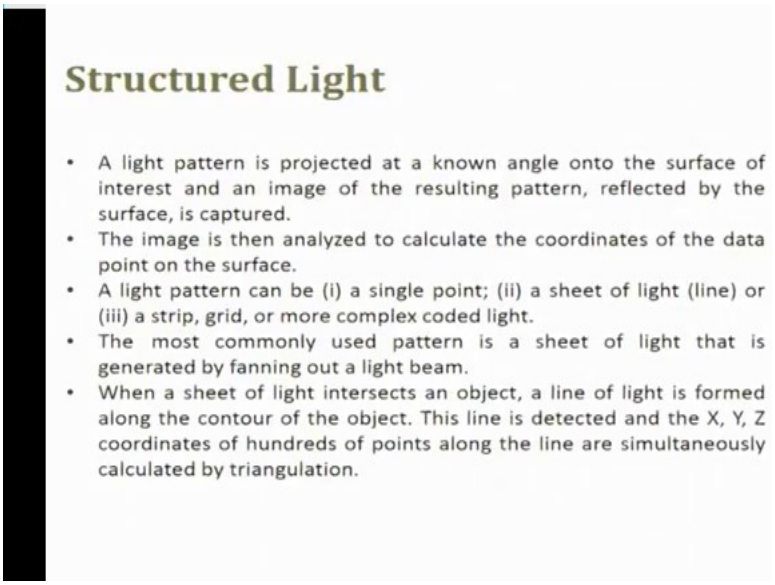

The next one is structured light, the structured light pattern is projected at a known angle on the surface of interest and an image of the resulting pattern reflected by the structure is captured. The image is then analyzed to calculate the coordinates of the data points on surface, the light pattern can be a single point, a sheet of light or a strip of light in a complex manner the most commonly used pattern is a sheet of light that is generated by fanning out of a light beam. So, then we try to get the x y z data.

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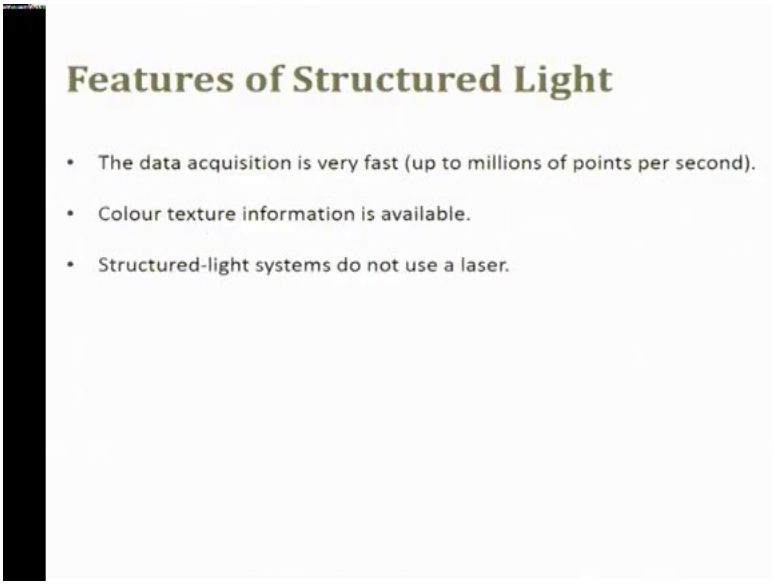

the data is acquired very fast, colour texture information is available, structured light does not use a laser. So, the maintenance is slightly economical.

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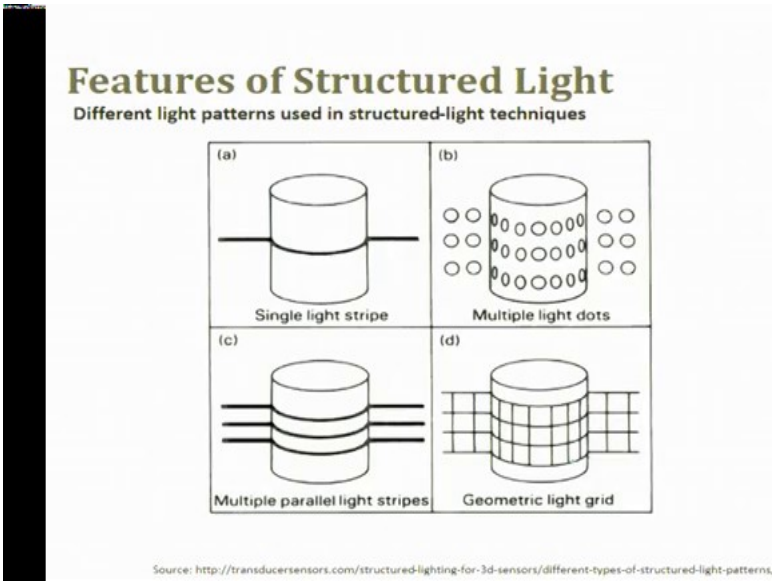

These are the different types of structured light, a single light strip then multiple light dots, multiple parallel light strips, geometric light grids. These are projected and then the details are collected.

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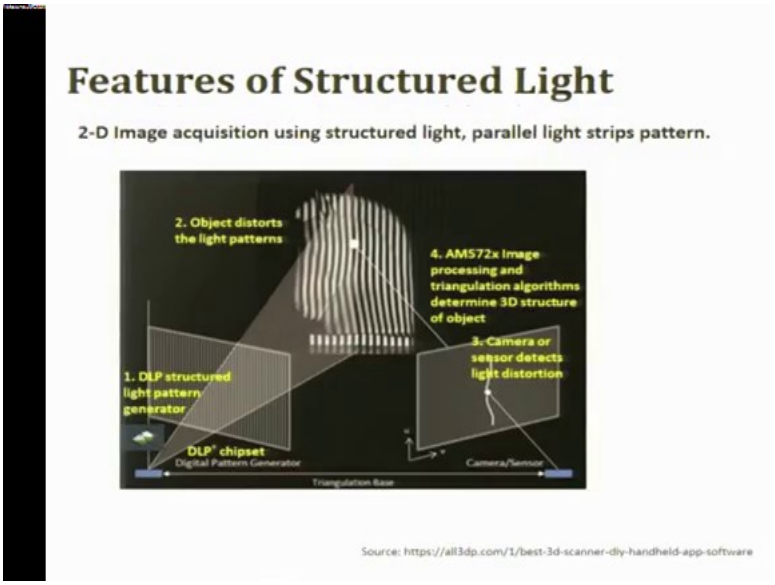

You can see a DLP structure, light pattern is generated, the light goes from here and then DLP is generated, then the object distorts the light pattern, the object distorts the light

pattern and then the camera on, the sensor detects the light and then the image processing and the triangulation algorithm determines the 3D structure of the object. This is how a structured light works for non-contact scanning.

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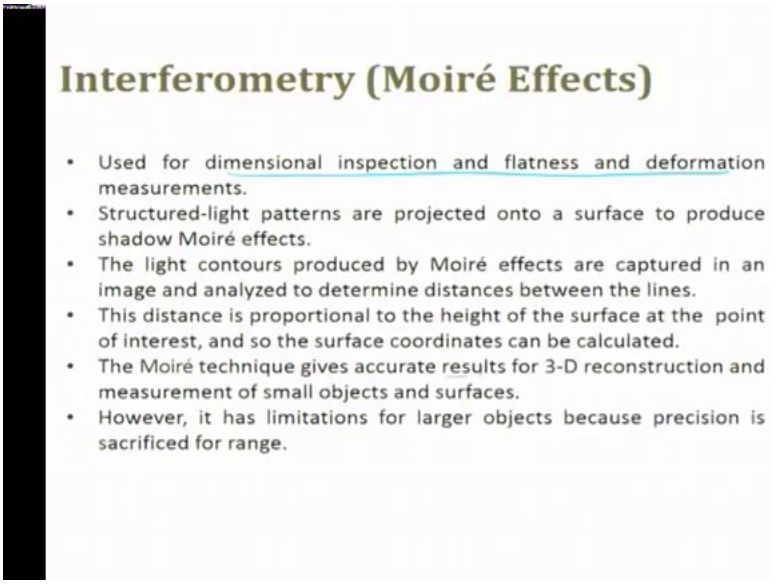

Moiré fringe patterns or interferometer used for dimensional inspection and flats and deformation patterns, we use Moire fringe patterns, We use Michelson's interferometer, which is used to measure the angular displacements that's what they are structured like pattern, are projected on a surface to produce a shadow Moire effect.

The light contour produced by Moire effect are captured in a image and analyze to determine the distance between the lines, the distance is proportional to the height of the surface at the point of interest. The Moire fringe technique accurately results for a 3D reconstruction and in gives you good results.

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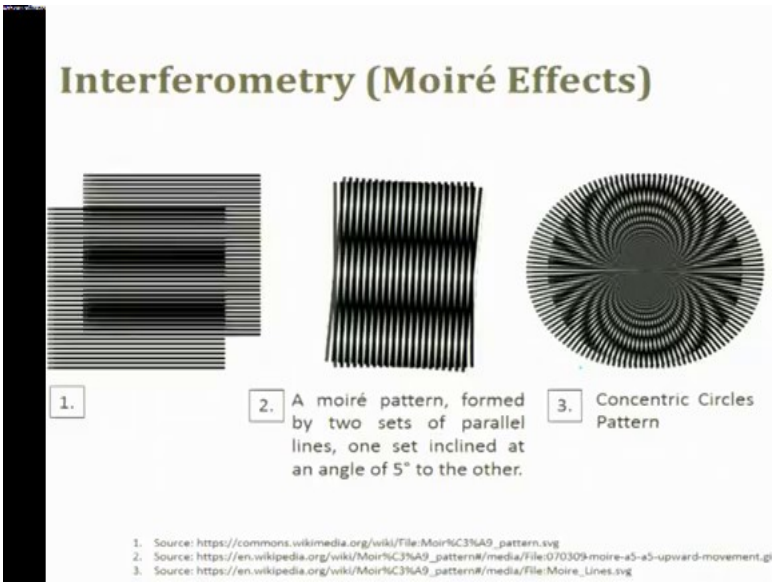

This is a typical Moire fringe pattern. A Moire fringe pattern form a two sets of line which is angled at 5 degrees, this is a concentric circle pattern which is made. You keeps growing and when you try to take the image of it from the image you can try to correlate and try to find out the 3D object.

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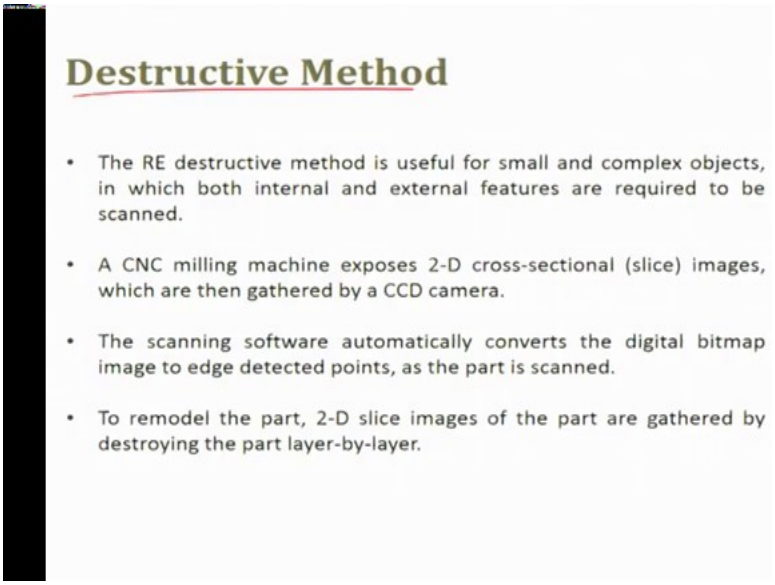

We will next see the destructive methods, destructive method is useful for small and complex objects, with which both internal and external features can be scanned.

we are trying to take an object, section the object and start doing CNC milling which exposes 2D cross section images which are then gathered by a CCD camera, then the scanning software automatically converts the digital bitmap image to the edge detection image and forms a part the model is remodeled and you get from slice by slice information.

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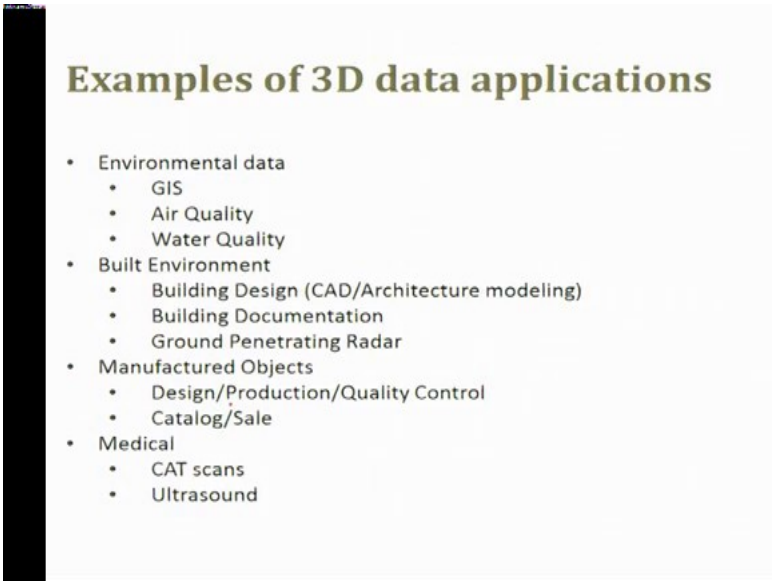

Here are the examples of 3D data application, environmental data, GIS, air quality, water quality is taken for 3D data, building data, manufacturing data and medical data all these things use 3D data application.

- Raw data components, there are raw data, texture, 2D image, spatial n dimensional image in terms of time and sensor data. So, you also have derived data, modeled data, technical data and you have bookmark data.

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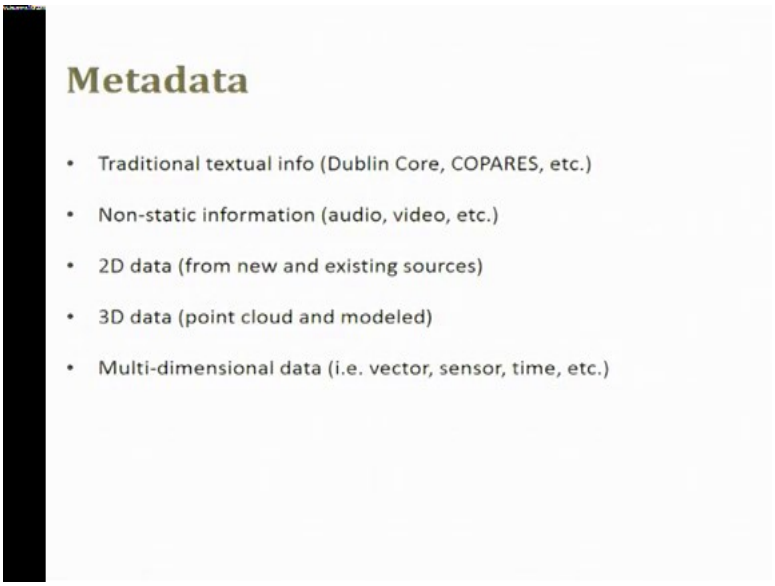

Here is some of the data which is already available, traditional texture information, non static information, 2D data, 3D data and multiple dimensional data, all these mixed data are available and they are used as part of reverse engineering.

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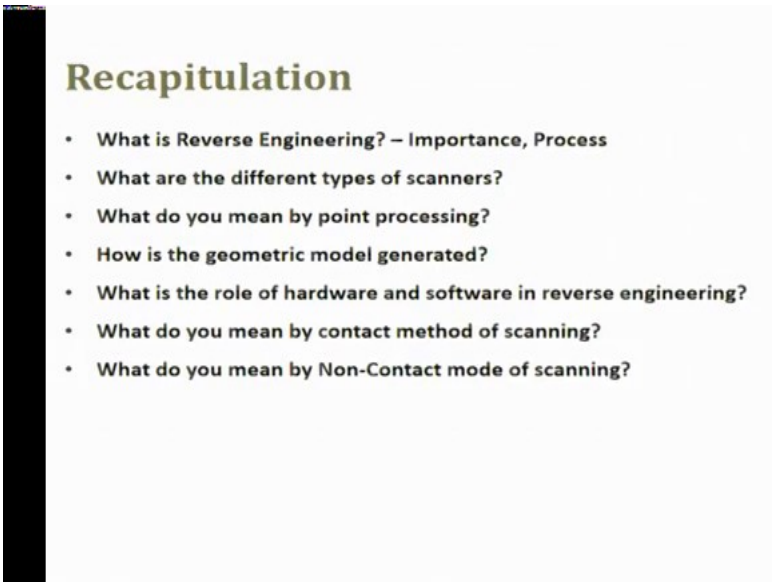

To recap what we saw in this particular lecturer is,

- What is reverse engineering? Importance, process?
- What are the different types of scanners?

- What do you mean by point processing?
- What is geometrical model generation?
- What is the role of hardware and software?
- What do you mean by contact measurement?
- What do you mean by noncontact measurement or scanning?

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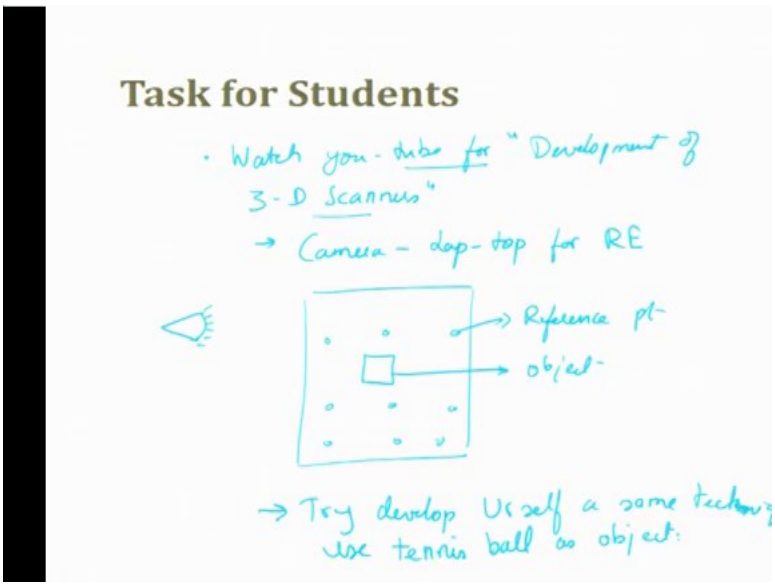

STUDENT'S ACTIVITY

The task for the students is going to be, watch YouTube for development of 3D scanners. here what they do is they use a laptop camera for reverse engineering. What do they do? They take a camera and then they try to keep an object, then they try to keep the object in a frame and in that frame, they try to have reference points, these are reference points. This is the object, they try to calibrate with respect to the reference points and then they try to go to the objects, scan the image of the object and try to get the data.

Watch that video and try to develop same technique, use tennis ball as the object and try to do reverse engineering and get the data.

Thank you very much.