Metal Additive Manufacturing
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Lecture 30
Reverse Engineering in MAM (Part 1 of 2)

Welcome to the next week of the course metal additive manufacturing, we have till now discussed multiple technologies and the processes which are used for additive manufacturing of the metals. Also, we have discussed some physics like solidification that happens when we try to develop the product or the component using additive manufacturing, then additive manufacturing of metal matrix composites, the in situ and other controls.

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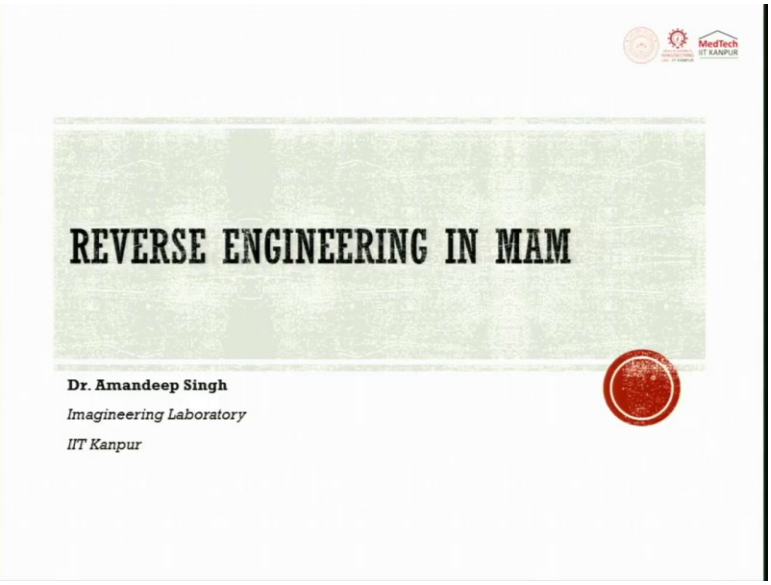

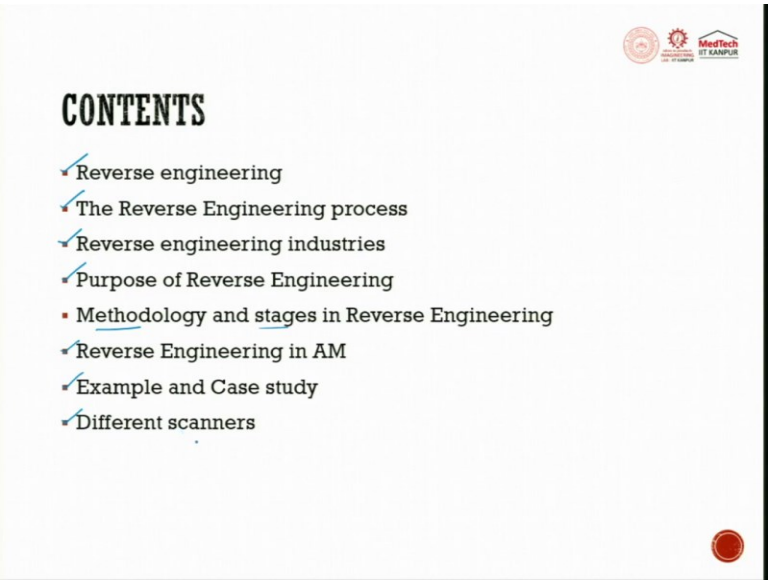

In this lecture, I would like to discuss reverse engineering used in metal additive manufacturing. And the contents of the lecture would go like this, I talk about what is reverse engineering, what is the process to conduct reverse engineering, the reverse engineering industries which have mutually taken the acumen to develop the products using additive manufacturing.

Then what is the purpose of reverse engineering specifically, methodologies and stages in reverse engineering then reverse engineering for additive manufacturing specifically, and examples would be taken to elaborate the things which are explained, then different kinds of scanners or the reverse engineering equipment that are in use.

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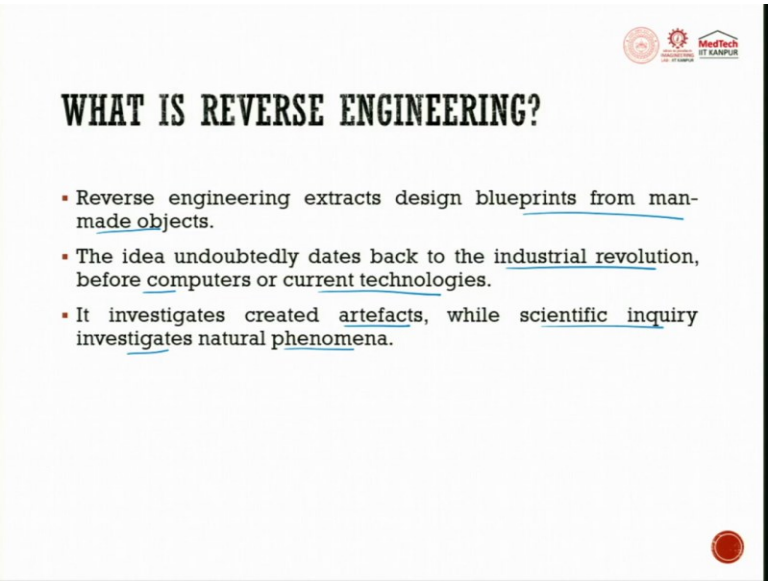

What is reverse engineering? Reverse engineering abstracts design blueprints from man-made objects, reverse engineering could be applied to any of the processes and if the products that we would have to replicate, for example, if you have a chair with you, you would like the carpenter to produce a similar chair, he will come he will measure the dimensions using the measuring tape, he will see what are the different shapes, he will try to replicate the same components and same parts of the chair and try to produce it for you.

If I am having a blazer, and I cannot visit my tailor once again I send my blazer to the tailor and tell him please make a replicate of this, what he will do he will take all the dimensions he will measure everything try to see what are the different aligns and he will try to produce that. This is reverse engineering when we are trying to produce a copy of an existing product or we are trying to study a product.

For example, the tailor would also like to teach his new students how to stitch a blazer what he will do, either he could start the former process. He can say, this is the cloth, the other are the cuts that you make, these are the shapes, and these are the stitching processes.

In other ways he can give them a stitched coat which is not in use, he can tell okay you please try to unstitch it and try to see what are the various curves, what are the various points there that you need to understand when you try to dismantle or unstitch a coat, so that is reverse engineering.

So, it is blueprints from the manmade objects, the idea undoubtedly dates to the industrial revolution itself before computers or current technologies. Now, software reverse engineering is also one of the processes that is the talk of the town, because softwares is also replicated and the similar kind of the form wherein the mobile phones also we receive.

So, it is analogous to scientific research, where a scientist tries to decode the atom or the mind. Reverse Engineering investigates created artifacts, while scientific inquiry investigates natural phenomena.

When we miss some knowledge, some ideas, some design philosophy, reverse engineering is used to understand how the product was developed, what could have been the processes in developing this product, some people will not disclose their information, sometimes the information is lost or deleted. So, reverse engineering has certain purposes that we will discuss when we go through this lecture.

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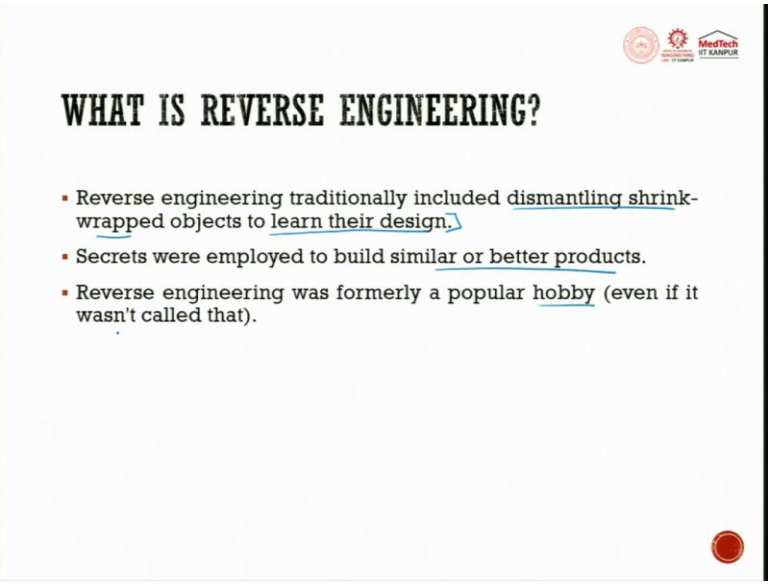

Reverse Engineering traditionally included dismantling shrink wrapped objects to learn their design. So, how the object is designed, to replicate that, to understand what are the different components of the assembly, what are the various traces that have been carried out to produce its objects, what will be the steps in the assembly, all these things are taken care of when we are trying to learn the design of the object.

The secrets were employed to build similar or better products. Reverse Engineering was formerly a popular hobby even it was not called that.

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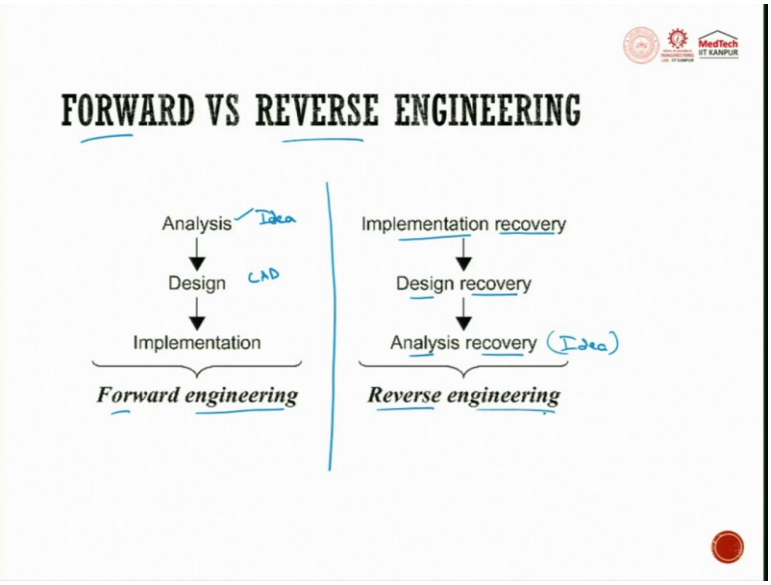

Now, two processes are there to learn the something to do or to build something obviously, the forward and reverse engineering, in the forward first we do analysis we try to put in mechanical engineering if we are trying to produce a product we try to first produce the idea, we try to generate the idea then we try to design it, this design could be in the form of CAD then we try to implement that there are three simple steps analysis, design, implementation, this is forward engineering.

What is engineering? Engineering is the application of the scientific knowledge that you have. Scientist tries to develop something novel, engineering tries to apply that information that scientists have generated.

Now, implementation of the product that is there, recovery from that and try to recover design from the implementation, then try to analyse what could have been the idea, this is reverse engineering. So, there is a clear delineation between how we go about and understand what is reverse engineering.

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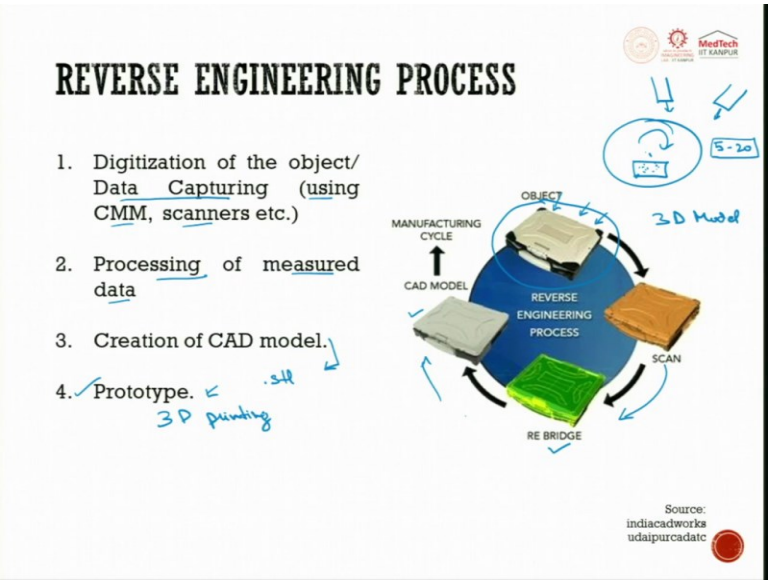

Now, a reverse engineering process typically involves these 4 steps, they are the multiple steps which are part of it each of these steps for example, digitalization in itself could have 10 tasks in it, but digitization of the objects that is a data capturing using the machines such as scanners, coordinate measuring machine, etc is step number one, the example which I have quoted that a tailor will take the tape and try to measure the dimensions of the cloth or the blazer that is already built, or the carpenter will also take the inch tape and try to measure the dimensions of the chair.

So, this is data capturing, he will know the dimensions on a paper, he will try to make a small drawing, small cuts, he will just mark the important points, way that things need to be properly set, this is data capturing, this is a very trivial example that I have given.

If I am trying to reverse engineer a product, for example, my complete laptop, I need to understand what are the components of the laptop before the component with different assemblies of those what are the different dimensions could be or I would say in general, if I need to just produce the outer shape of the laptop, this is an object how could this be done, the scanners try to produce the 3D model of this.

The 3D scanners are there which we will discuss then these 3D models when we try to scan through these have certain noises, certain missing points, how to treat them that is known as data

cleaning that also takes place then we try to build a bridge of that these RE bridge and we try to then develop a CAD model.

Now, processing of the measured data, processing of the measured data implies the data that is scanned there would be multiple replicates of the model or of the data that is scanned for example, if this laptop is to be scanned using a 3D scanner, it would be scanned maybe 20 times. It would be kept on a plate that would be rotating, here the laptop would be kept.

So, the scanner light would try to emit the laser or also try to reflect it back to the receiver and the cloud data is generated. This does not happen in one go, these rotations might be 5, might be 20 or so. So, at each rotation we are having some information of the product and this information is to be collected into a single RE bridge or single model CAD model that we need to have finally, as our reverse engineered soft prototype.

The creation of the CAD model would be the next step then the prototype development, prototype development is a thing, but we try to have a STL file from here and try to 3D print it using multiple processes that we have learnt in the previous lectures.

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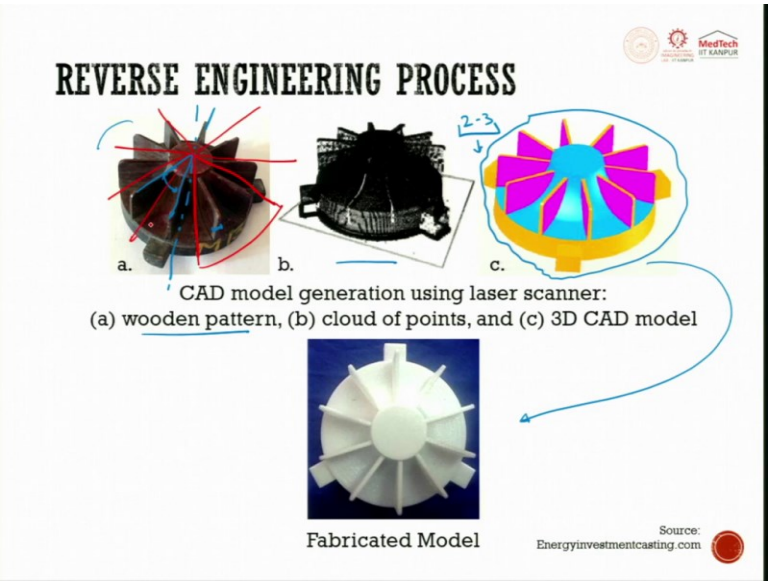

Now, again a typical example, this is a wooden pattern of an impeller when we try to reverse engineer it what we get is the cloud data, in the cloud data you can see the dots are only there. The dots are the points which have been captured using this 3D scanner, these dots are then

converted into mesh, that also we will discuss the after 2, 3 iteration or 2, 3 steps in between here so, we get the CAD model, the CAD model has the complete shape of the original pattern that we have.

Now this CAD model, it is 3D printed here. It could be 3D printed in Polymer, in metal, in whatever material we require. In this case, this is a complete model. There could be certain ways when you try to scan for example this is completely symmetrical about its axis. So, what we can do, we only need this angle, and we need to understand this thickness of the fins of the impeller.

So, we can even scan half of the object for example, only half of the object or I can even scan only a small portion such as this portion only. And using the array command in my software, I can produce the array of these and try to have my complete object, it depends upon the resources that you have, reverse engineering any of the processes that you are trying to implement, the time is one of the factors and time is proportional to the money that is incurred in it.

So, to minimize the time of reverse engineering to get the best information, the quality of the data that you have has to be legitimate to have the CAD model proper. So, there are multiple ways to deal with it.

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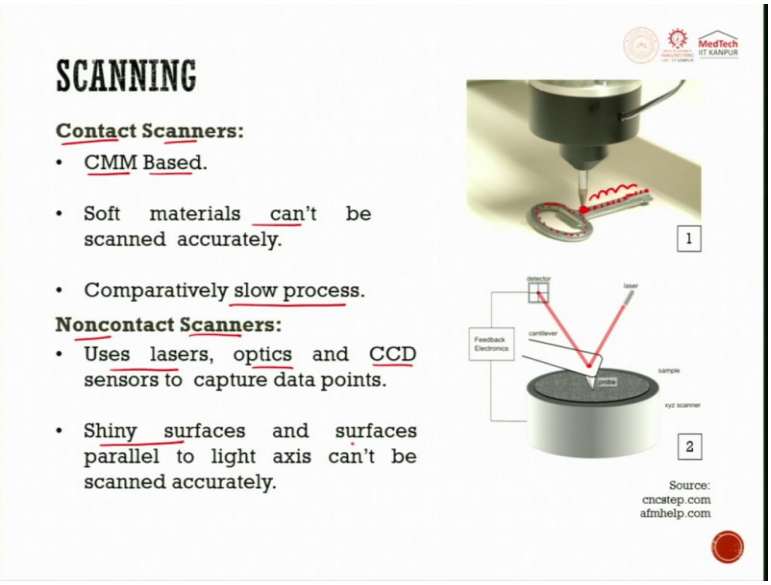

Now, the scanning could be conducted using two types of the scanners. One is the contact type and other is a noncontact type scanners. Contact type scanners obviously, using a measuring

tape, we have to completely touch and have the measurement this is the contact type of the measurement, noncontact type would be the scanners if they get the data digitally without having the actual contact with the object that is being scanned.

In the contact type scanners in mechanical, we have coordinate measuring machine-based scanners which are the major contact type scanner for example, there is a probe here, there is a sapphire tip here which is a soft tip. It keeps on having the data at certain points 1 2 3 4 5 6 7. At this point, we can have more closer point 8 9 10 11 12 13 14. All these points would be gotten then these points would be connected then it can have points here.

Then this kind of this scanner would only get the information while touching the component that is under the scan. The soft materials cannot be scanned, there are certain limitations because if the soft materials will be touched for example, the food items the bread or the cloth, the probe will just go inside or try to move, will not have the exact information. It is a comparatively slow process because the mechanically the components have to move from one place to another and this takes its time.

Now, there are the alternatives for these noncontact scanners, which uses lasers, optics, and CCD sensors to capture the data points. Now, one of the drawbacks in the noncontact scanners would be it cannot scan these shiny surfaces because when the light falls on the object, it is reflected back, the shiny objects will obviously have some reflection index so, the light will not be giving the exact information.

Similarly, the black objects might absorb the light. So, shiny surfaces or black surfaces cannot be scanned with this for that we have a pretreatment before scanning that is there, we try to do so the lasers, optics, then charged coupled devices that is CCD this all helps us to get the data. Similarly, surfaces which are parallel to the light axis cannot be scanned accurately using the noncontact scanners.

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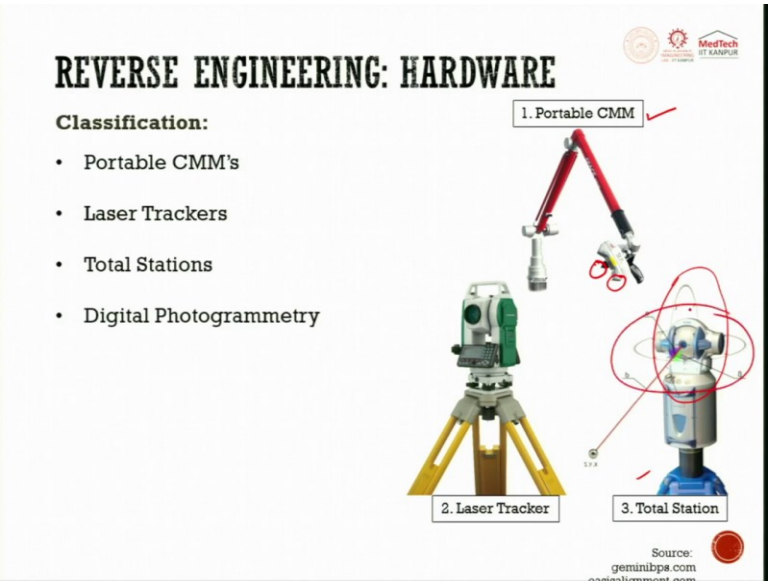

Now, if I try to classify the hardware of the reverse engineering, majorly we have the coordinate measuring machine systems which are the here, the portable CMM system which are also known as the arm kind of the score coordinate measuring systems. So, this is an arm so, it works on the polar coordinates. So, wherever we touch it, it could have a touch kind of the system you can see a probe is there, also a light could also be there that could help us to understand the system to work in both the contact and noncontact systems.

Now, laser trackers are also there, laser tracker that are generally used in civil engineering to have the measurement of the large distances, total stations that also there. It is a total station that tries to have the information around, this is 360 degrees in as one degree of rotation, another degree of freedom is this direction. So, also this could also be rotated so digital photogrammetry is also one of the processes that uses different hardwares.

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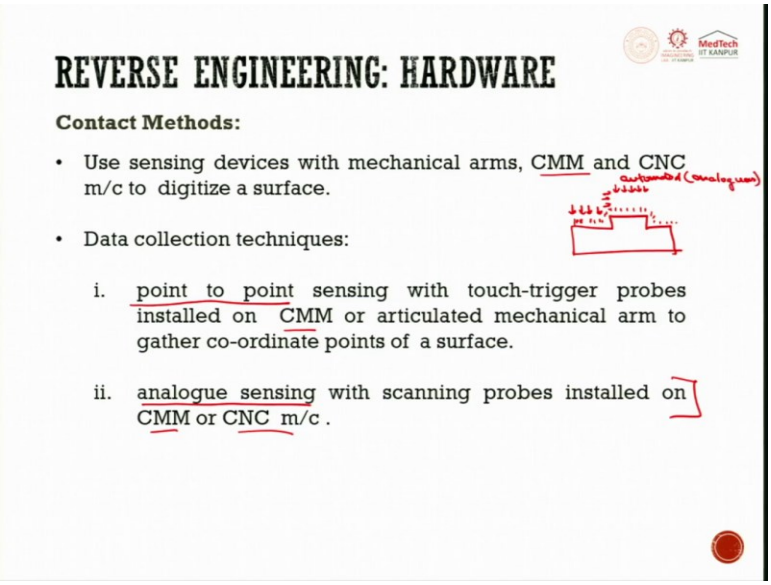

The contact methods, now use sensing devices with mechanical arms, coordinate measuring machine and CNC machine to digitize a surface, so data collection techniques are of multiple types, majorly two of them are point to point sensing and analog sensing.

Points to point sensing is when I manually try to scan my object from one point to other, these are the points that my scanner is trying to capture. Here point to point is manually being moved from one point to another using a joystick that is an attachment to the current coordinate measuring machine.

So, in that contact kind of sensors, these point to points sensing touch trigger probes installed on CMM or articulated mechanical arm to gather coordinate points of a surface. So, CMM provides more accurate measurement data compared to the articulated arm. But I would say complex shapes are difficult to be scanned using this.

Next is the analog sensing, analog sensing is an automatic system in which the sensing happens through CMM or CNC machine or in analog sensing the scanning probe provides a continuous deflection output that can be combined with machine position to derive the location of the surface. The scanning speed in analog sensing is up to 3 times faster than point to point sensing because this is automated in this we just make the CMM system to understand okay you have to

start scanning from here it will keep on scanning the points when it reaches this area, it will understand this it cannot go above.

So, it will start taking points this direction that it will not find any area here, any object in front of it, it will start standing in this direction, but this is an automated system, automated that is called we call it analogous.

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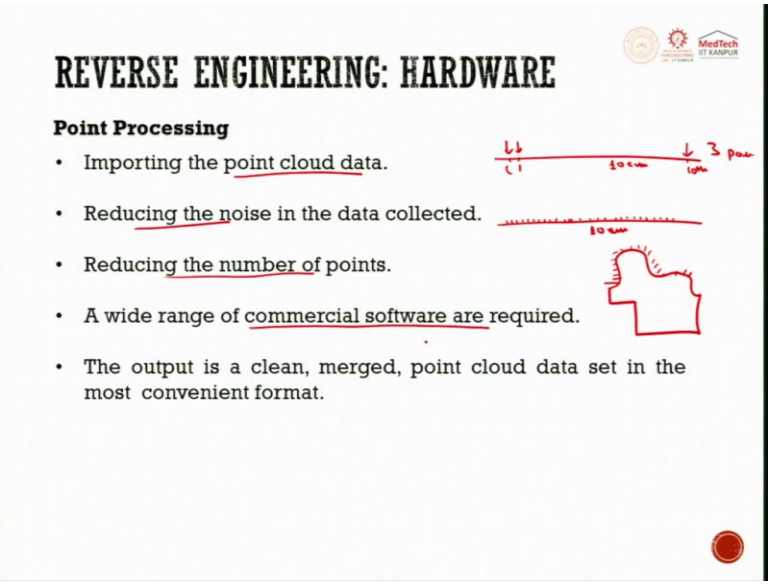

Now, point processing system that is used to import the point cloud data that reduces the noise in the data collected, that reduces the number of points as well because manually we can definitely select which points are important for example, this is a big, this big length, I have taken 2 points here, I would just need one more point to understand this is the length.

So, this is only 3 points, we will get the whole information of the surface and definitely these coordinates would be marked, it might be 10 centimeters or so. So, we took it in the first centimeter we took it in the last centimeter that is a 10th one or 3 dimensions make me, gave me the dimensions or the length of that is one of 2 dimensions, 2 points could even give, in the analog system if I have made it to have the resolution or the point distances 1 mm or maybe 2 mm.

So, it will take number of points here, so this becomes a slower system at certain points, if the dimensions are longer, but if the shape is complex something like this, in this the analog system will move faster it will take its points by itself.

Now, these tasks of measurements using CMM are performed using a range of predefined filters, already multiple scans are sometimes needed to ensure that all the required points are scanned and a wide range of commercial softwares are required sometimes to clean the data as well. Now, output is a clean merged point cloud data set in most convenient format.

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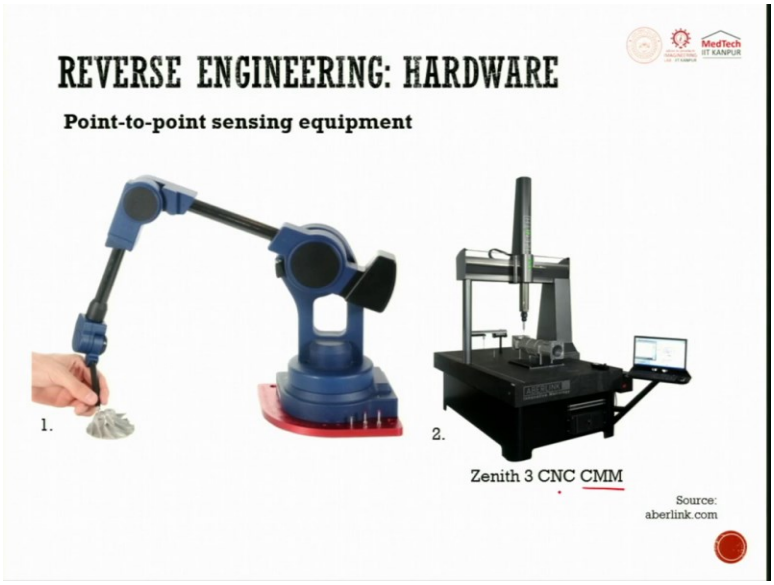

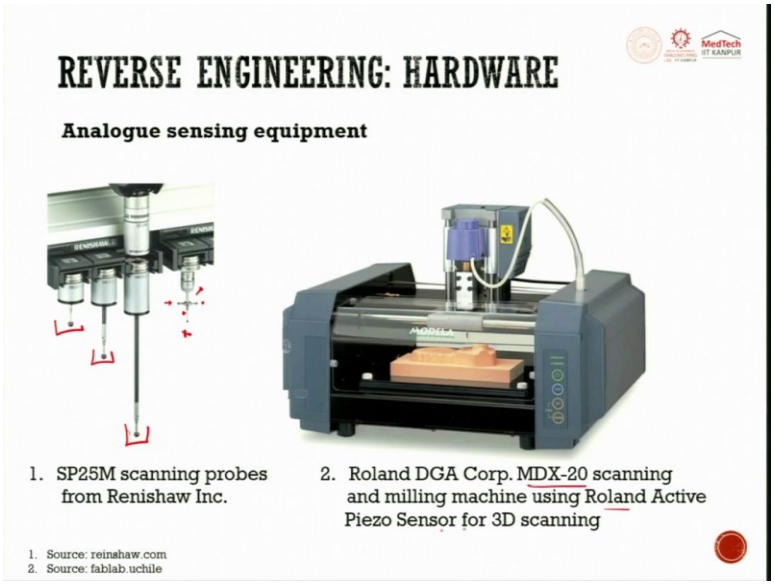

Now, point to points sensing equipment in this we have the CNC coordinate measuring machine. Just to show you I have put this Zenith 3 CNC CMM as an example, other than that, we have the SP 25 M scanning probes from Renishaw Inc. You can see different kinds of probes are there for the deep to reach surfaces, this kind of probe could be used.

These are the probes for the surfaces, which are even less deep. There is a probe that has 1 2 3 one on the other side, 4 and 5 different directions of the points or endpoints that they have different kinds of probes that could be used. Now, this is the Roland DGA corporate MDX-20 scanning and milling machine, which is using Roland Active Piezo sensor for 3D scanning. So, this is also a kind of CMM machine.

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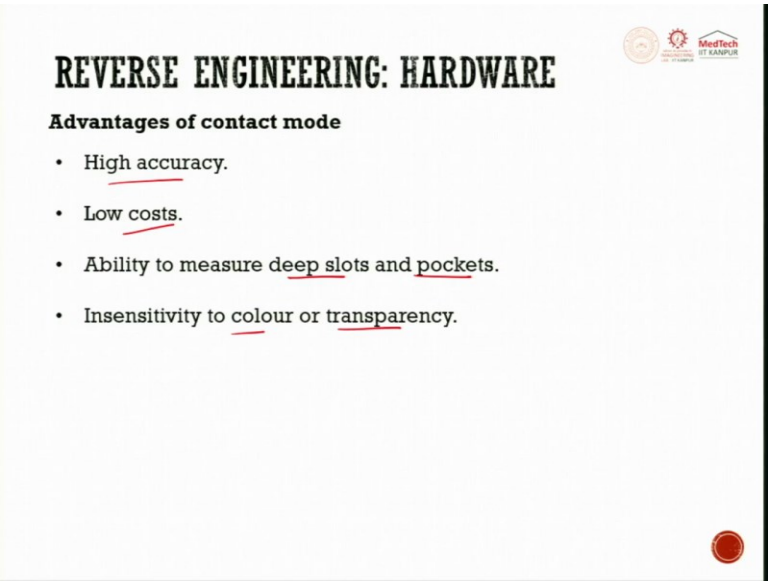

And advantages of the contact mode of the scanning is it has high accuracy because it is all contact we know where the points are there and the points are recorded in the Cartesian coordinate system in general.

So, we exactly know what information what data point is there, data cleaning is very minimal here, then the costs are low for the scanners because these are the contact kind of scanners, we do not have much sophisticated softwares in between. The ability to measure the deep slots and pockets is possible using this.

Sometimes the light does not go very deep. So, these deep slots are taken using the longer probes that we have and insensitivity to color or transparency or so transparent objects, the shiny objects, black objects are difficult to be scanned using the noncontact type of scanner because the light is the source of the scanning.

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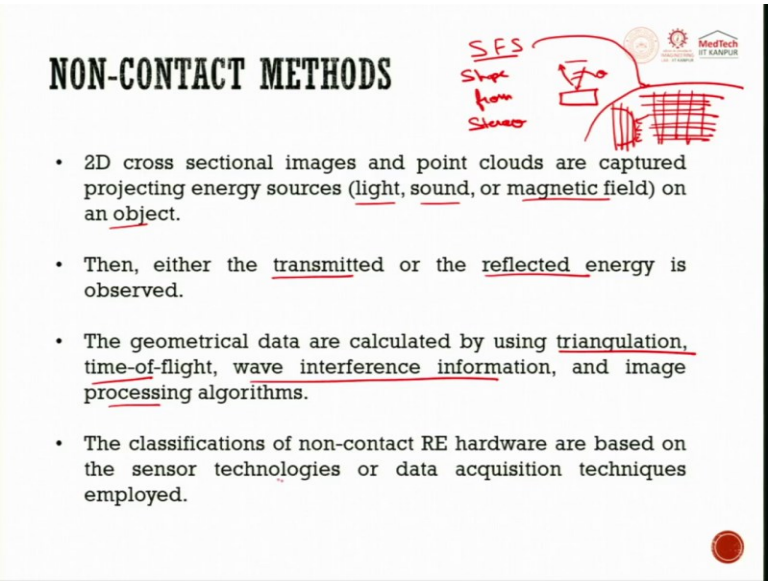

Now, noncontact methods include 2-dimensional cross section images and point to point clouds are captured projecting energy sources. Energy sources could be light, sound, magnetic field, or an object.

Then either the transmitted or the reflected energy is observed, it is either transmitted through the object or it is reflected back, geometrical data are calculated by using triangulation, time of flight, wave interference information and image processing algorithms, so triangulation method when the light falls to an object or on an object return back, this makes a triangle, this angle of the triangle for each point gives me the data that is recorded here.

Now, this is triangulation method when the light is reflected back, it could also be transmitted through for example, this is a grid that we have light made to transmit through this object, it will fall on the object so, this grid as a 2 dimension will give me shape at this point, the second one and third point and so, I can even get the information in this way, this is known as shape from

stereo method. Now, classification of the noncontact reverse engineering hardware are based on the sensor technologies or data acquisition techniques employed.

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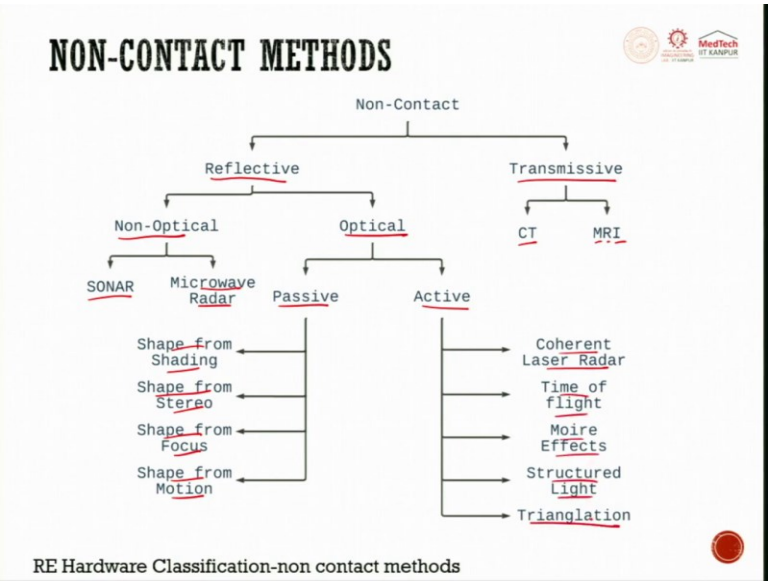

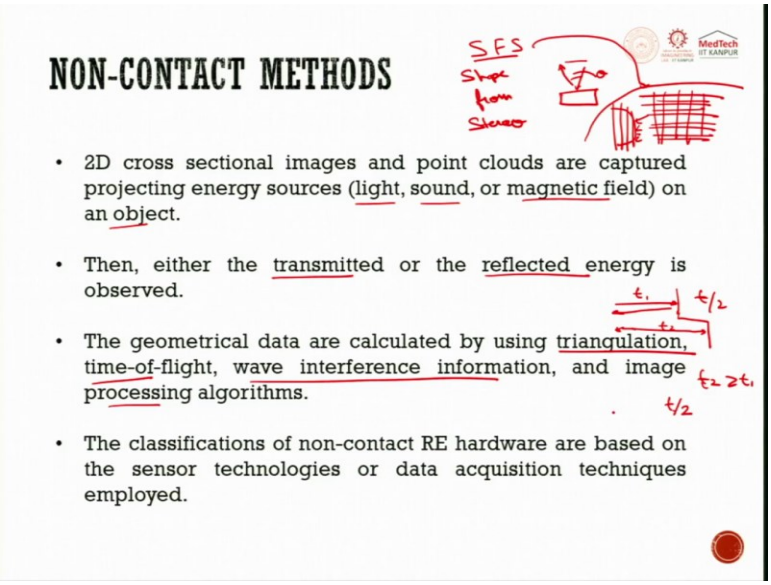

The non contact methods are of multiple types. We have reflective types of technology and transmissive technology, transmissive technology is, the CT and MRI majorly used in medical devices. Here is Computed Tomography and magnetic resonance images, these are the transmissive technologies and reflective when the light is reflected back different methods which

I have just mentioned here, the triangulation, time of flight; time of flight is when the light goes and it comes back.

So, this is time t of going and coming back. So, t/2 is a time when light comes back to a farther object for example, to farther dimension this time would be for this time is t_1, this time is t_2 that is larger here $t_2 > t_1$ and the time of flight is t_1 or t_2, the dimension could be taken by considering that time t/2, t_1/t_2, t_2/t_2 like wave interference information, image processing different kinds of methods are there, those methods are the non optical and the optical methods.

The non-optical method shown are, microwave radar technologies which are used then the optical method, passive measurement or active measurement could be taken, in the passive measurement. I just mentioned shape from stereo, shape from shading, shape from focus, shape from motion, so these are not a direct measurement as I told you the light just goes and tries to put a shape through a 2 dimensional area that we have. Now, active methods are coherent laser radar, time of flight, Moire effects, structured light and triangulation.

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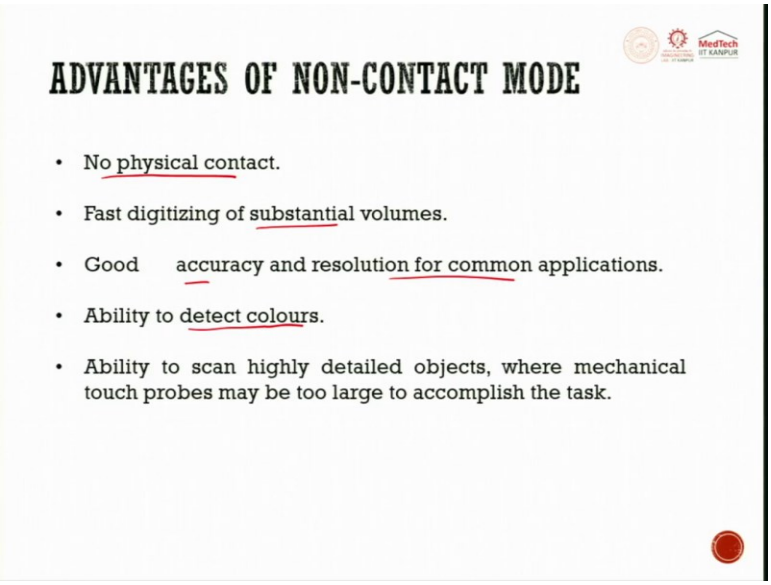

Generally, there is no physical contact that is one of the advantages of the noncontact methods of the digital of the reverse engineering. Now, fast digitization of the substantial volumes is there, good accuracy and resolution for common applications is there, ability to detect colors is sometimes also there.

Now, there are different kinds of the scanners available like Faro gage arm that can also let you know what are different colors.

If I am trying to scan this object, it can give me okay this is one object, this is the second component of that. So, it can give it in a different color. So, these different colors could be detected here, the ability to scan highly detailed object because the scanning resolution in the noncontact scanners could go up to microns, so we can have more detailed of the object that we are trying to scan to intricate strips would also be scanned easily. So, where the ability to scan highly detailed objects is there when mechanical such probes may be too large to accomplish this task.

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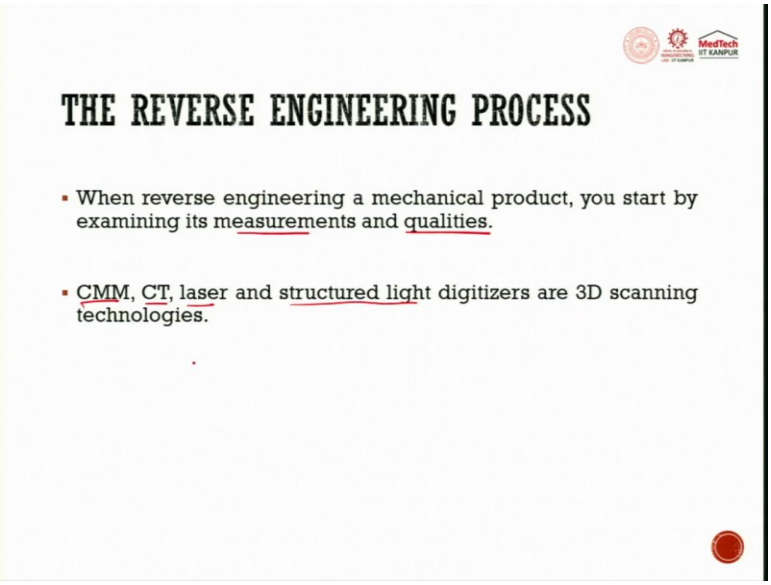

So, when reverse engineering a mechanical product, you start by examining its measurements and qualities, which means during the analysis, during the collection of the data, you may have width, length, height of the products components, because these dimensions affect the performance.

Sometimes we need to employ the 3D scanning for these measurements. We can automatically lock the product characteristics from 3D Scanners into the data basis.

Now, CMM, CT, laser, structured light digitizers are 3D scanning technologies, which are already mentioned recording the relevant information. One can build a CAD design and analysis for the development which I have already discussed.

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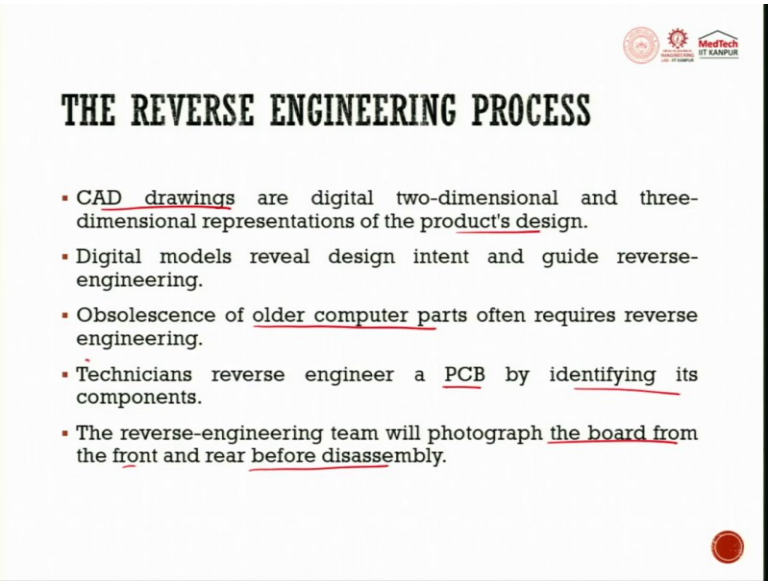

These CAD drawings are digital, 2 dimensional and 3-dimensional representative of the product design, the CAD drawings.

The digital model reveals design intent and guide reverse engineering, obsolescence of old computer parts often requires reverse engineering, old computer parts sometimes are to be reverse engineered to understand what the components of this are and because these are obsolete, these are out of the data, these are to be updated. So, to understand them reverse engineering is required, technicians reverse engineer a printed circuit board by identifying its components, reverse engineering team will photograph the board from the front and rear before disassembly, this is regarding PCB only.

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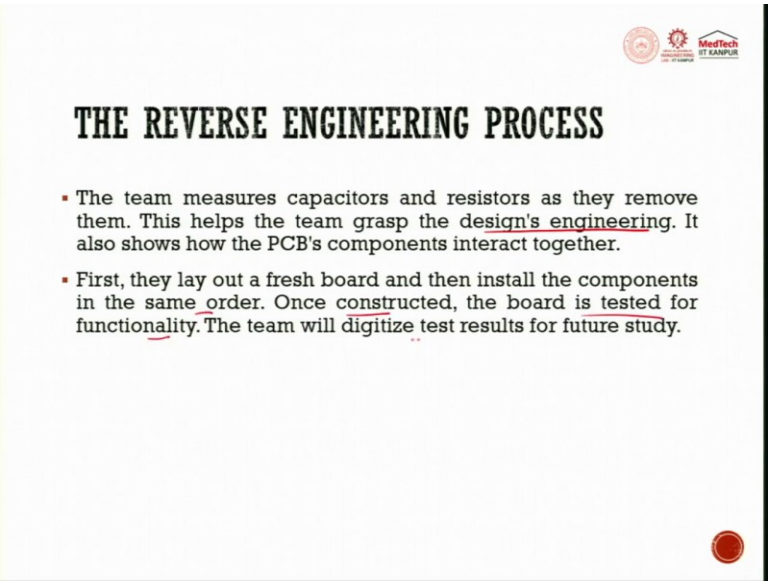

The team measures capacitors resistors as they remove them, this helps the team to grasp the designs engineering, this is a PCB printed circuit board design again, it also shows how the PCBs components interact together. First, they lay out a fresh board, then install the components in the same order. Once constructed, the board is tested for its functionality, the team will digitize results for future study just to take an example, the printed circuit boards or the motherboards of the computers when we try to see them.

So, how are the components being arranged here and what do we try to do to have the more space to install some more small components there. This is required when we try to reverse engineer something.

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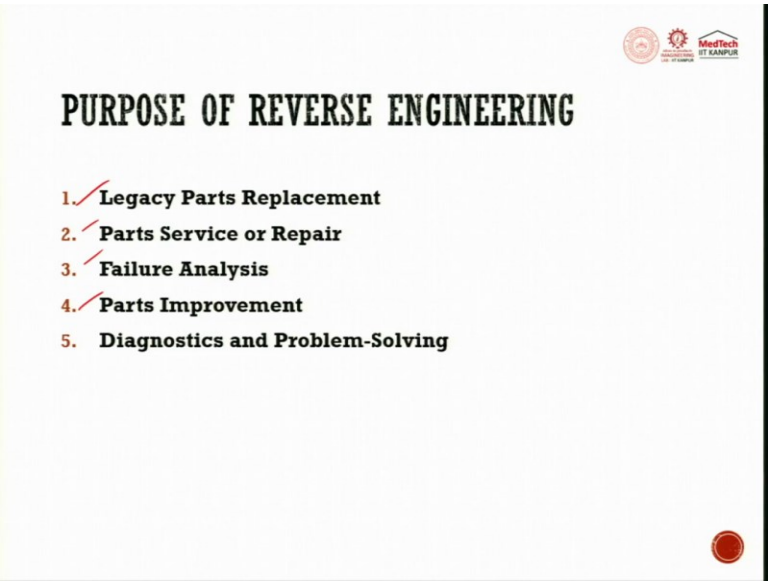

Now, legacy purpose of reverse engineering is specifically we have a legacy for the plot replacement, we have parts service or repair, then we have failure analysis of the components improvement in existing components try to understand which are the specifically weaker points or weaker components which are there which can be replaced or improvement could be made diagnostics and problem solving.

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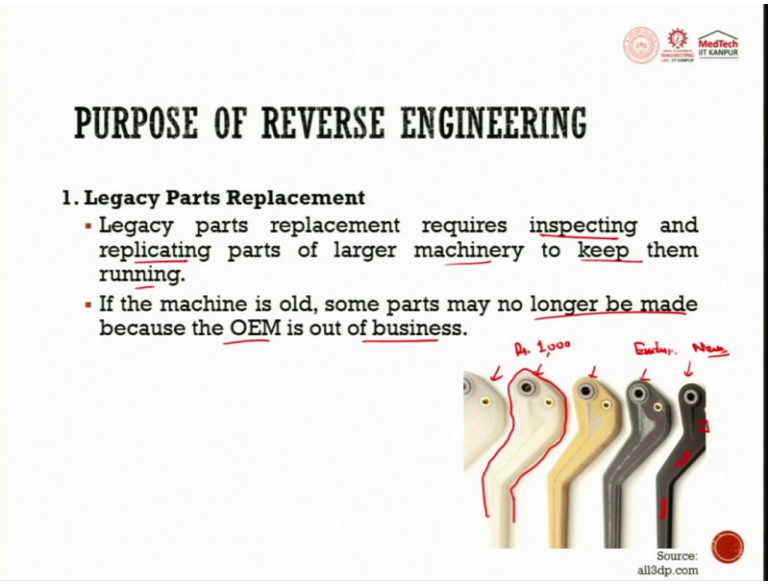

Legacy of the part replacement when I say, the legacy part replacement requires inspecting, replicating parts of larger machinery to keep them running. Now, a factory is big engine compartments keeps the conveyor systems functioning through each shift sometimes each machine part needs to be replaced or sometimes a small machine parts is to be replaced.

So, if the machine is old, some parts may not be longer to be made from the original equipment manufacturer so, this is out of the business so metal additive manufacturing helps us to develop the components which are out of the production from the original equipment manufacturer and we try to replicate them. So, the factory could buy a new conveyor system, but replacing the defective element is preferable.

So, small this is the replicate of the components which are produced from the polymer just to have a test of the shape of the component because this is not much expensive. For example, this component if developed through the polymer additive manufacturing, it could have been costed maybe 1000 rupees but we try to test this shape exactly the dimensions then we go to the metal part and we try to produce the final component which is reverse engineer that, this is an existing component. This is the new component that is being built. This is how we go about.

Now, the topology optimization could also now come into play when we try to reduce the volume of this component. For example, this inner volume might not be required, only a small connection or a mesh could do the help. So, those small updates and optimizations could definitely help here.

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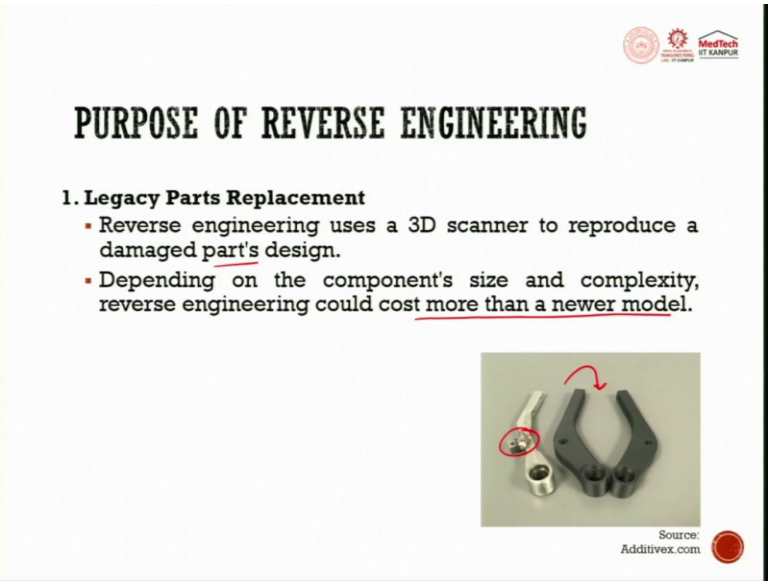

The reverse engineering uses a 3D scanner to reproduce a damaged part's design depending on the components size and complexity, reverse engineering could cost more than in newer models sometimes.

So, this is the component that is defective now, this is a reverse engineered part that is produced. So, once we have produced a digital duplicate of the original design, and replicated the part we can reuse it. Reverse Engineering helps us to replicate parts that work in our mechanical setups, even if the original produces are gone.

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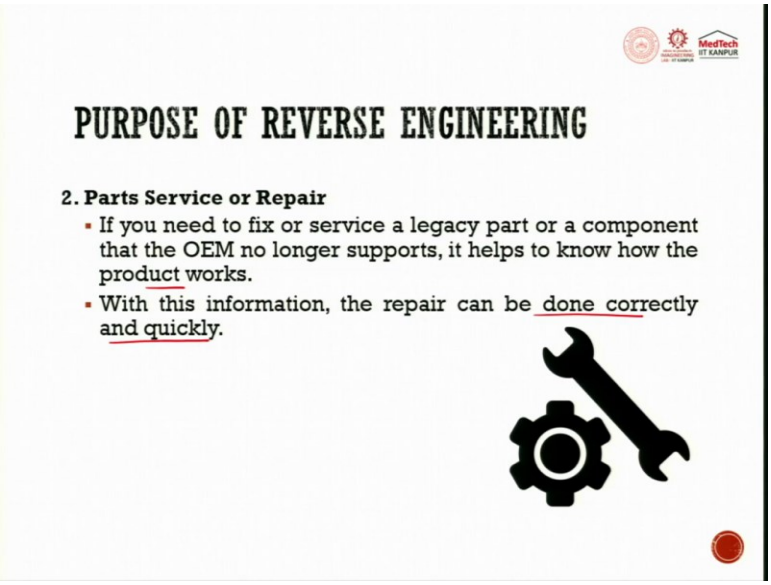

Now, next is the part's service or repair. If you need to fix a service, a legacy part or a component that the original equipment manufacturers no longer support, it helps to know how the product works. So, with this information, the repair can be done correctly at least to understand what different parts of the machine are, we need to dismantle the machine and understand the original make, how was it developed, this is also reverse engineering.

For example, if there is no design document, a company may use reverse engineering to make them. So, with the information one gets from the reverse engineering, he or she can figure out which parts are needed to be changed or to be fixed or which is a bit of the problem. It can also help to fix something by giving us a better idea of how to get to or to remove or to replace a component.

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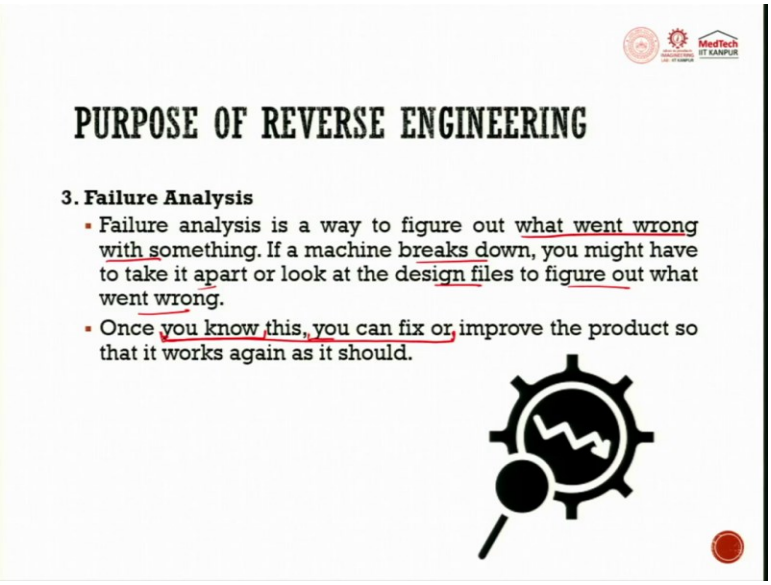

Now, next a failure analysis is also one of the purposes of reverse engineering. Failure analysis is the way to figure out what went wrong with something if a machine breaks down, you might have to take it apart or look at the design files to figure out what went wrong. So, once you know this, you fix this, so, nothing can be manufactured unless it is measured, nothing can be fixed unless it is understood, nothing can be retrofitted unless it is rectified.

So, first we need to have the correct measurement and correct understanding. So, that means if we know this, if we know the dimensions, then only we can fix this. So, reverse engineer really helps us to understand what dimensions, what shapes, what different intricate points, or what are the weaker points.

For example, these locks are the mouse, the weaker point here would be this lock, lock of the mouse that helps me to get the cover back over encased.

So, to understand what the weaker points are, that helps us to gain the information that how a product could work again. So, by using reverse engineering to look at the product, or the broken parts, or the bad designs, we can understand what new improvements could be made looking at a digital design files made with reverse engineering that can help us to find flaws in a piece of equipment and figure out how to fix it.

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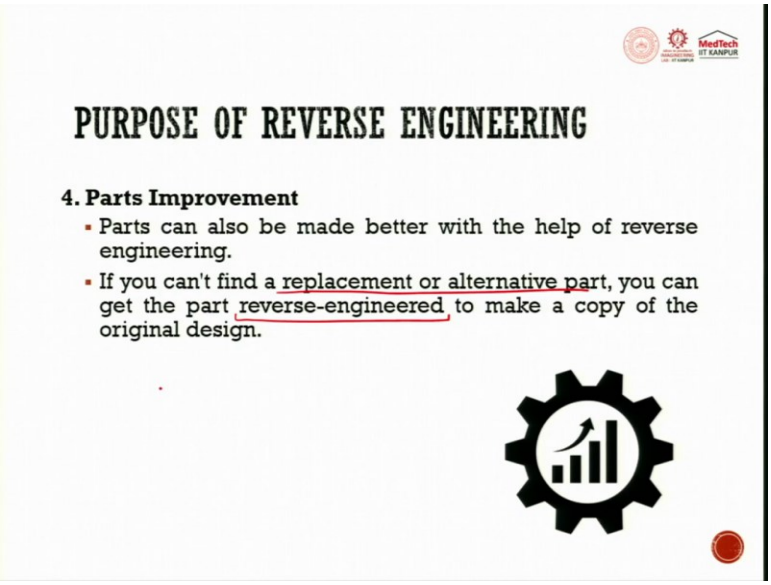

Now, parts improvement, which we just discussed is also one of the purposes, parts can also be made better with the help of reverse engineering. So, after figuring out what part is broken, and why did it broke, what were the weaker points, one might need to replace it and taking into account the weaker point could be improved here.

So, it might be a time to upgrade the component now. So, if you cannot find a replacement or an alternative part, you can get the part reverse engineered to make a copy of the original design, then we can modify that design to make it work better if the machine needs its joints or valves to be stronger, then broken parts will be measured and redesigned with the thicker metal or stronger joints through reverse engineering you can figure out what needs to stay same and what could be changed.

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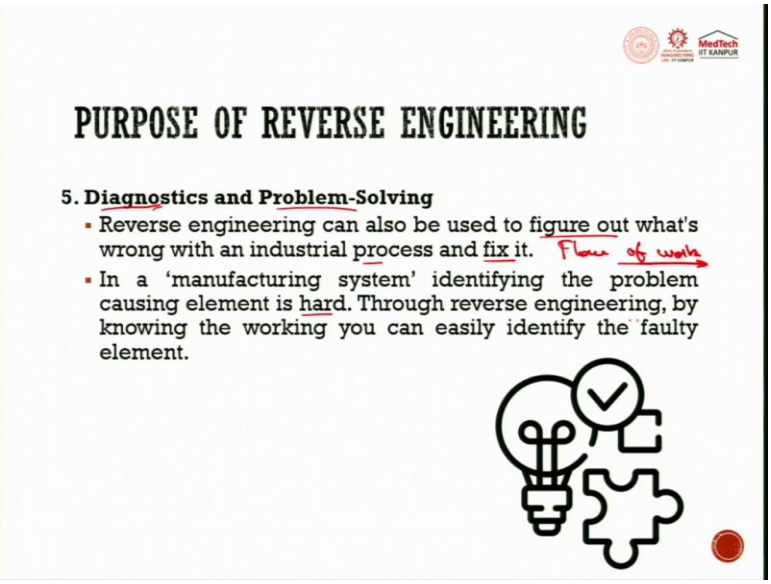

Now, diagnostics is also one of the major purposes, diagnostics and problem solving. Reverse engineering can also be used to figure out what is wrong with an industrial process and how to fix it in a factory setting, if a function is broken or not working, it can sometimes slow down the flow of the work.

So, the flow of the work has to be continued, has to be keep on going. So, that is why reverse engineering helps us to have a clear diagnostics and solution to the problem that sometimes come. Now, in a manufacturing system identifying the problem causing element is hard, through reverse engineering by knowing the working you can easily identify the faulty element.

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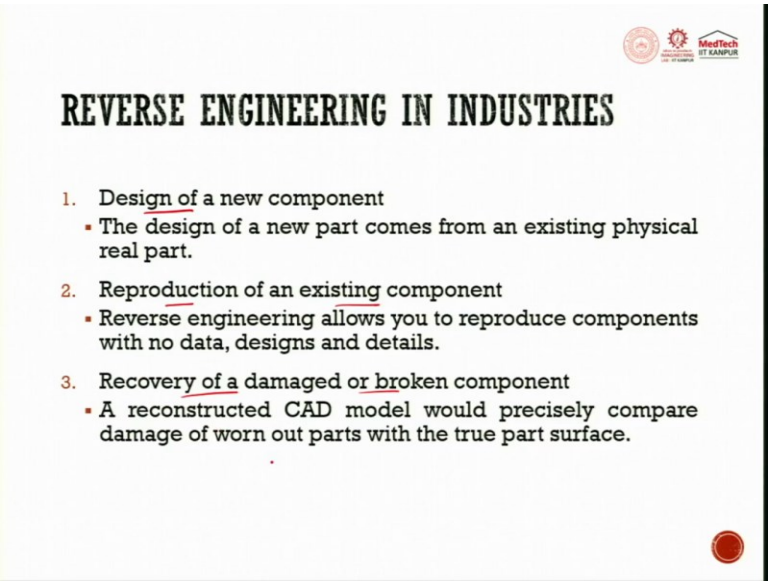

Also, we can design a new component in an industry, reverse engineering is used to design a new component. To design of a new component part comes from an existing physical real part then, we can have a reproduction of an existing component. Reverse Engineering allows you to reproduce components with no data, designs and details, recovery of a damaged or broken component. These are the actual applications that happens in the industry a reconstructed CAD model would precisely compare damaged or worn out parts with the true part surface.

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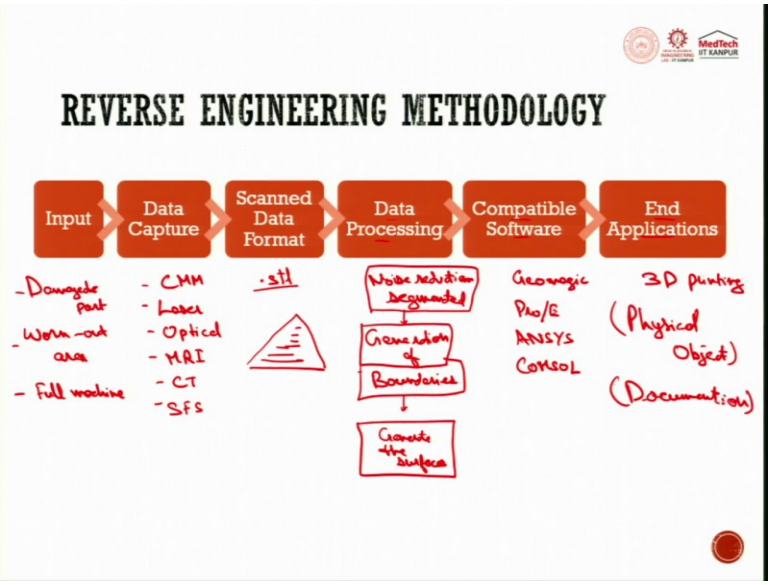

Now, reverse engineering methodology has certain steps. The input data capture, scan data format, data processing, compatible software, which helps us to produce the CAD model, then end applications compatible software would help us to have the proper solid 3D CAD model. Then end applications would be having a 3D printed object in this case where the input would be the component or the object that is being reversed engineered that is under the study.

So, this could be its damaged part then or a worn out area of some part or maybe a full machine for which we are trying to design how the machine was built. Now, next is data capture. For data capture, we have different scanners like we have coordinate measuring machine, we have the laser scanner, we have optical scanner like again the transmissive and reflective kind of systems then we have definitely MRI, CT and the shapes from stereo and so on.

The scan data format in generally, the format for 3D printing is STL format in which we get the layer-by-layer component for example, this is a component. So, layer by layer, the component would be that is majorly developed using the STL file, this is the format because I am talking only about additive manufacturing here. So, STL format is there, data processing is the most important part, data processing is cleaning of the data.

In the next part of this lecture, I will have a laboratory demonstration in which the 3D scanning would be demonstrated, we will try to explain the components of one of the 3D scanners and so, we will try to say how the cleaning of the data happens there.

So, data processing needs the noise reduction. When I say noise, there are extra or unwanted points which are there in the unwanted clouds. So, these are also reduced or these are sometimes segmented, noise reduction is one part. Then we generate processing the boundary curves, generation of boundaries.

Once the data noise is reduced, the points are still there, and from these points, we try to generate the boundaries of the major components. From these major components, these are the complete boundaries then from the major components, we try to generate the surfaces.

The compatible softwares are always required there could be softwares for example, the Geomagic, just a bit branches of it then Pro E, ANSYS etc. ANSYS is a analysis software, then COMSOL sometime some scientific input is required, we need to conduct small simulation over

it, try to understand the failure, try to understand the behavior of the object against specific parameter for example heat or strength, these things could be taken care of.

Then we have the end applications. In this case, we have a CAD system and we have the CAM system or we have the Computer Aided Engineering system. So, we have our 3D printing.

So, we actually have the physical object here, it could be physical object, it could be the documents. Sometimes a physical object is not required the purpose of reverse engineering is just to understand the process and keep the record with us so that in future whenever required that could be used to develop the physical objects or to understand the failure or the broken part that if it is there.

So, then documentation, so these are the outputs here. So, this is the reverse engineering methodology naturally. So, with this, I will close the first part of my lecture on reverse engineering in metal additive manufacturing. I continue this lecture on reverse engineering and I will discuss the steps, the details of the steps and the laboratory demonstrations in the next lectures. Thank you.