**Laser Based Manufacturing**
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**Module No # 06**
**Lecture No # 19**
**Laser Scanning Stereolithography**

Hello everyone. I welcome you all to the second lecture of Week 6 of NPTEL MOOC course on laser-based manufacturing. In this week, we are studying additive manufacturing technologies. Lasers are playing an instrumental role to get the required product quality and productivity in additive manufacturing processes. In our previous lecture, we have seen the stereolithography. And in coming lectures we are studying the SLS, that is a selective laser sintering and selective laser melting. In this lecture, we will be continuing our discussion on stereolithography, its variants, and then we will see the applications of these techniques as well. Let us begin our discussion on the stereolithography in a little more detail.

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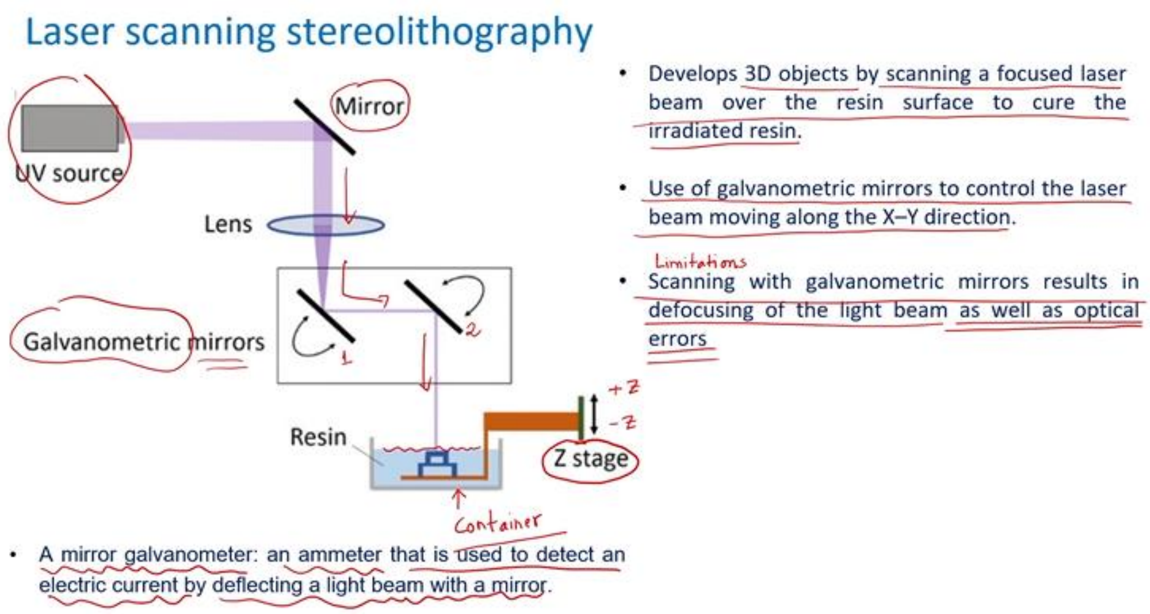

As I mentioned right now, we have seen the laser scanning stereolithography, its principle of operation. We have also seen various CAD CAM aspects related to generation of the 3D parts by slicing the 3D digital model into 2D drawings or 2D digital models.

There are certain variants of stereolithography process which are being used in the industry. Some of them we will be seeing right now. on your screen you can see arrangement of a laser scanning stereolithography system. here we are having a stage. stage is an electromechanical device. This electromechanical device is being controlled by CNC based controller. And on this stage, we are having the development of our final work part. Then we are having a container, this is the container in which the resin is kept in the form of liquid. this is liquid resin. And we are applying the laser beam energy over this liquid resin at designated part and that part will get cured. This stage is having the capability to move in positive Z and negative Z direction. We are having a UV source. And by using the UV source we are getting the laser beam energy and to get the laser beam energy we are using a set of mirrors and these mirrors are Galvanometric mirrors. by using this Galvanometric mirrors these are the electrical controlled mirrors and the moment or the rotation or the location of this mirrors is being continuously being monitored by using an ammeter. This ammeter is located in this galvanometric mirror, and by just observing or by monitoring the current which is flowing when the mirrors are getting rotated, they are getting relocated or they are getting placed as per the required direction.

this galvanometric mirror is helping us to irradiate the required zone required place required location of the resin which is there in the container. We are focusing the required amount of laser beam energy by using another mirror. This is called as Bender. Actually, this is bending mirror which is providing us the laser beam energy at an angle of 90°. Then the focused laser beam energy will get at the spot.  here we are getting the laser beam energy and by having the required rotation of these mirrors, we can maneuver or we can move the laser over this surface. this surface at any point we can reach by having the relative motion between this galvanometric mirror number one and mirror number two. So, in this way we can develop 3D objects by scanning a focused laser beam over the resin surface to cure the irradiated resin. Here we are using a galvanometric mirror, as I mentioned to control the laser beam which is moving along X and Y direction, and the height of the product will be controlled by the stage that is moving along the Z direction.

However, there is a problem or there is a limitation of this particular arrangement, and that limitation is that the galvanometric mirrors are defocusing the light beam. when we are maneuvering the laser beam over the resin surface, due to this movement of the laser, there may be chances of having defocusing of the laser beam energy. And when there is a defocusing of the laser beam energy, we may not get any form heat flux over the laser surface. We may not get uniform heat application over the surface. As there is non-uniform heat application there may not be proper curing of the resin surface. Also, there may be some sort of optical errors as well and due to this non-focusing and optical errors we may not get the required quality of the 3D product which is getting developed. here, as I mentioned, the galvanometer is an emitter that is used to detect the electric current by deflecting a light beam with a mirror. And the deflection of the light beam takes place when the beam of the light is projected on a mirror.

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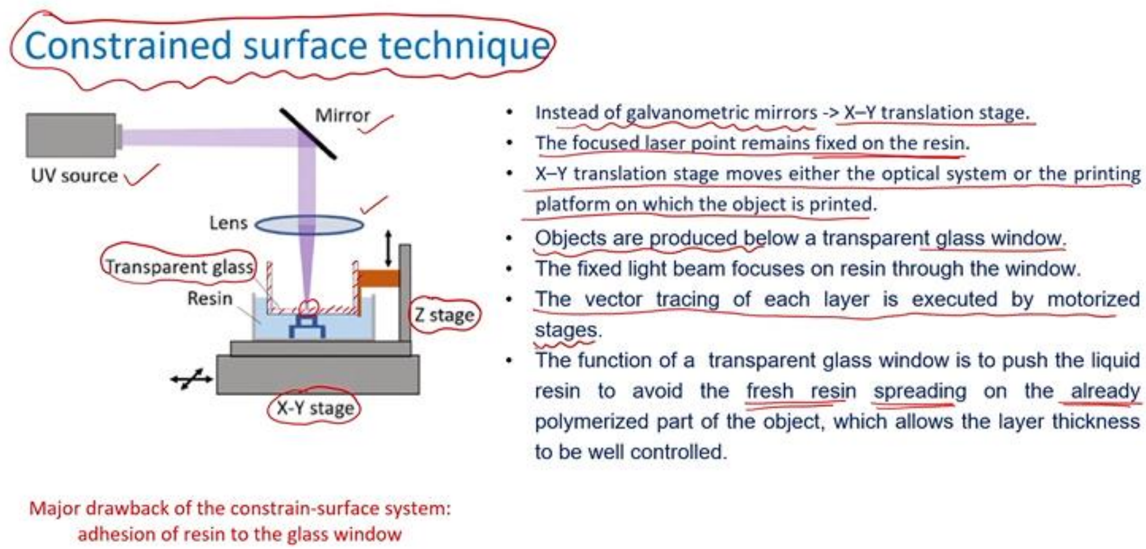


Now this problem of defocusing and optical errors can be solved by making the laser beam stationary and we can move the substrate. that particular arrangement can be seen on your screen. here you notice a Z-stage Over the Z-stage we are having the container, this is the container. Inside the container there is the liquid resin and the container and the Z-stage the total assembly is put on XY-stage. we are moving the XY stage. the substrate is moving in XY plane as well as it is getting raised along positive Z direction and it will also get lowered in negative Z direction.

In addition to the container we are also using transparent glass. And there is a regular arrangement of UV source, a bending mirror and a focusing lens. these are the typical elements which are here as well - UV source, mirror and lens, through which we are getting the focusing of the laser beam at the required spot. But you notice here we are using a transparent glass and this transparent glass is allowing a uniform pressure that to be applied on the surface. when there is a curing is occurring. to have the uniform curing and there should not be spilling of the liquid resin over the cured surface immediately, a transparent glass arrangement has been done. here the same things are noted. instead of galvanometric mirrors we are using XY-translation stage. The focused laser point remains fixed on the resin. this point is fixed on the resin. XY translation stage moves either the optical system or the printing platform on which the object is printed.

Objects are getting produced below the transparent glass window. this transparent glass is having window through which we are getting the required irradiation. The fixed laser beam focuses on the resin through the window. And the vector tracing of each layer is executed by the motorized stage. the movement of the product which is given in the form of vector and that will be carried out by using the motorized stage. The function of the transparent glass here is to push the liquid resin to avoid fresh resin spreading on the already polymerized part of the object.

as I mentioned, once we cure one layer, we are trying to avoid immediate spreading over of the liquid over the resin, which is getting polymerized. during the process of the polymerization, if fresh liquid resin will come into contact, it may spoil the surface. To avoid this, we are using a transparent glass with the window. However, this type of arrangement is also having the problem of adhesion of the resin to the glass window. Here we are securing the polymerized surface from the liquid resin. But there is adhesion of the liquid resin with the glass. And due to that it is finding difficult to raise the transparent window in a proper fashion in upward direction and that is again creating certain problems. So, as we are constraining the surface, this technique is called as constrained surface technique.

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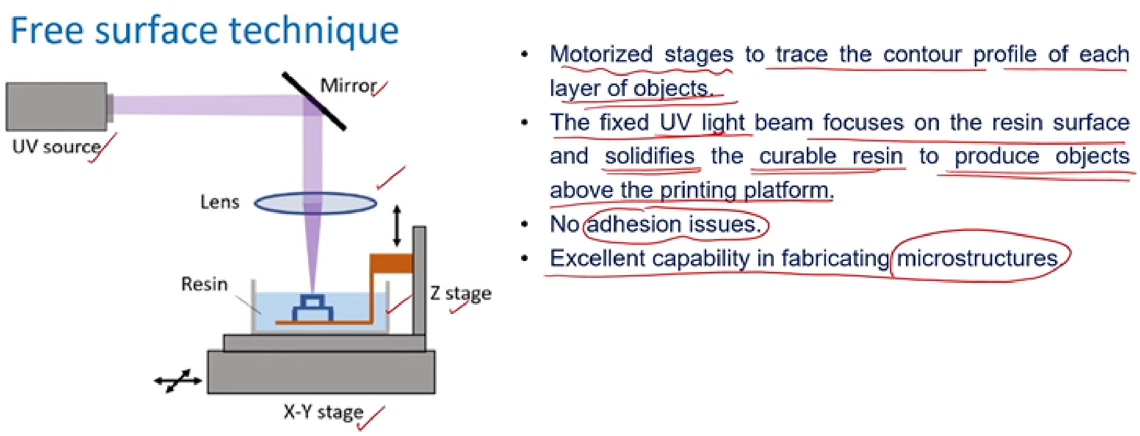


Now, the problem of constraint surface technique is the sticking or adhesion of the resin with the glass surface. That can be avoided by just removing that glass panel which is having the window. Then we can have a free surface technique. We are getting the surface free from any constraint. Being applied by the glass surface or the glass arrangement with the window. The schematic of the same has been there on your screen. So here we are having the stage. There is XY-stage along with the Z-stage, with the same work elements - the container resin, then the focusing lens, the bending mirror, and he UV source.

But you notice here we do not have the glass arrangement which were constraining the surface from getting sprayed by the liquid resin. as I mentioned, we are having a motorized stage to trace the contour profile of each layer of the object. The fixed UV light is getting focused on the resin surface and it is solidifying the curable resin and then we are producing the objects above the printing platform. There are no adhesion issues, as we are removing that glass part, there are no adhesion issues and we can have excellent fabrication of microstructures using this kind of arrangement.

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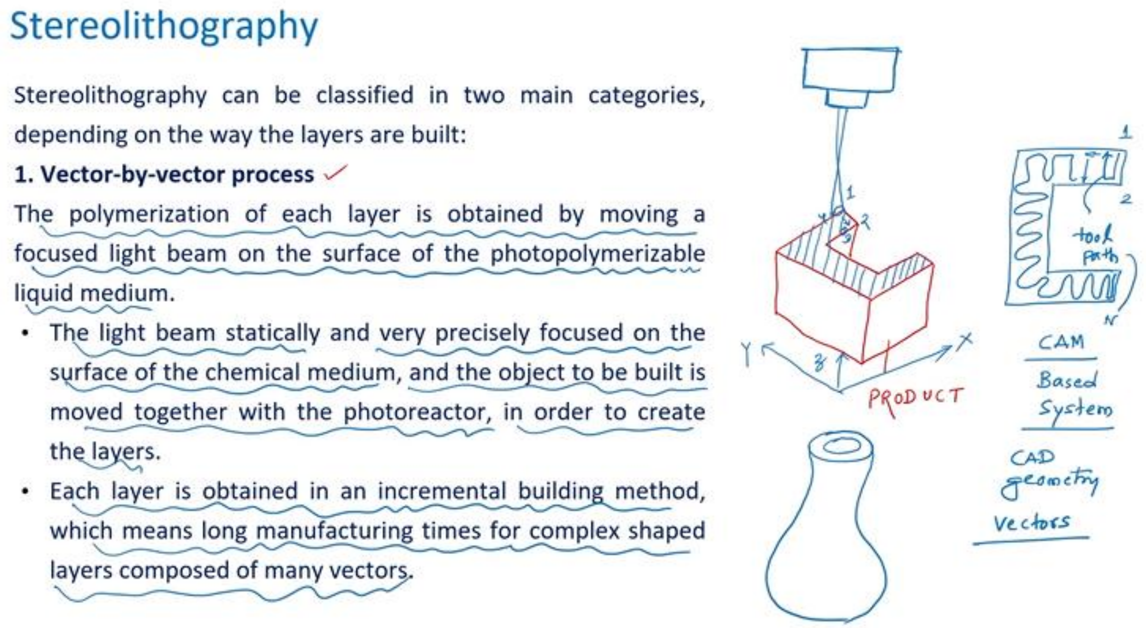


Fine! Let us see how we can classify the stereolithography based upon its irradiation strategies. there are basically 2 strategies or two approaches being used to classify the stereolithography. The first approach is vector by vector processing. let us see what is the meaning of vector by vector processing? Consider we want to develop a product very similar to this. So, this is the product that to be developed by using additive manufacturing technique. And for this purpose, we are using a laser beam. I am just drawing the laser beam over here. I am avoiding the other essential elements such as the mirrors and all. here the purpose is to scan the surface by developing certain vectors of the laser moves.

this is the laser height and we have seen various arrangements to get the laser beam, which is to be irradiated in a particular direction and the direction is the vector by vector thing. In this case we are generating this 2D surface in layer by layer manufacturing. the laser will come over here or it will start its journey from this point, point number one, two. the laser will come and it will start its journey here. And then it will move to point two, then point three, four. And in this way, if I try to plot the movement of the laser, it will follow a certain path. And that path is, may be a zigzag path or it may be contour parallel path.

if suppose this is the point one, and point two. the laser will come over here. Then it will move in this direction. Then it will move in the horizontal direction and come back. in this way the laser will get moved and that will be decided by the tool path of the laser.  ultimately it will reach here. this is the tool path of the laser beam irradiation which has to be decided by the CAM based system. And this CAM based system is working based upon the CAD geometry. And CAD geometry is generating the vectors. The CAD geometry is helping to generate the vectors and by using these vectors we are just tracing the path of that area.

we are filling the area by tracing the laser beam in a vector by vector manner. Here in an accurate way, we can carry out the polymerization, but this entire process is time taking. in vector by vector processing the polymerization of each layer is obtained by moving a focused light beam on the surface of photopolymerizable liquid medium that is a liquid resin medium. The light beam statically and very precisely focused on the surface of chemical medium. that we have noticed that the light beam is statically maintained its position. But the relative motion from point one to point n will be carried out by movement of the substrate or the product in XY-direction by using a set of stages that we have already seen in our previous slides.

And the object to be built is moved together with photo reactor in order to create the layers. Each layer is obtained in an incremental building method, which means that the long manufacturing times for complex shape layers composed of many vectors. this is a very simple geometry that we have seen. Consider we want to develop a very complex 3D geometry. Certain portion which is having a very complex surface geometry, vessel of this shape for exam. this is an artifact and we have to develop this by using the 3D printing operation. The geometry of such product is very complex. Or you can take the example of turbine blades as well, where the geometry is very complex. And to develop such kind of complex shape surfaces, or fuselages of the aeroplane. When you want to develop such shapes, then it is very difficult. We have to generate many vectors and these many vectors are filling the area and the movement of the vectors or the movement of the laser according to the vector is very time consuming.

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## Integral process

- Advantages over vector-by-vector process:
  - ✓ No unwanted polymerizations due to thermal effect: the light flux density arriving on the surface of the photopolymerizable resin when projecting the image of a complete layer is low, compared to the one of a light beam accurately focused in one point.
  - ✓ Integral processes are fast -> because the irradiation of a complete layer is done in one step, whatever its pattern may be, whereas moving the photoreactor in vector-by-vector stereolithography is slower -> leads to long building times.

To solve this issue, there is another process that is called as integral process. here the idea is to polymerize the complete layer in one go. a complete layer is polymerized in only one radiation. In only one irradiation the complete layer will get polymerized. The layers are cured over their entire surface in one step. whatever the shape it may be, the entire shape will get polymerized in only one step. And the time needed to polymerize in one layer is independent of its complexity. there is no matter what the complexity of the 2D shape is, in one go the laser will apply the UV light. And it the surface or the resin will get cured. the integral process is offering certain advantages over vector by vector process.

There is no unwanted polymerization due to the thermal effect as we have seen that the laser is moving along the vector that we are defining. But there may be chances of having the thermal effect of the moving laser over the surface. this kind of unwanted polymerizations are certainly avoided in the integral process. The light flux density arriving the surface of the photopolymerizable resin, when projecting the image of complete layer is low. in integral process, the energy that we are applying, the flux that we are applying is comparatively low. And that's why we are saving the unwanted portion undesired portion to get polymerized. In comparison with the vector by vector process, the integral process is fast because of the irradiation of complete layer. as I mentioned right now we are completely irradiating the surface in one go. That is why the integral process is quite fast. Whereas the vector by vector process is having long building times. That is quite obvious because of movement of the laser for a longer duration of time.

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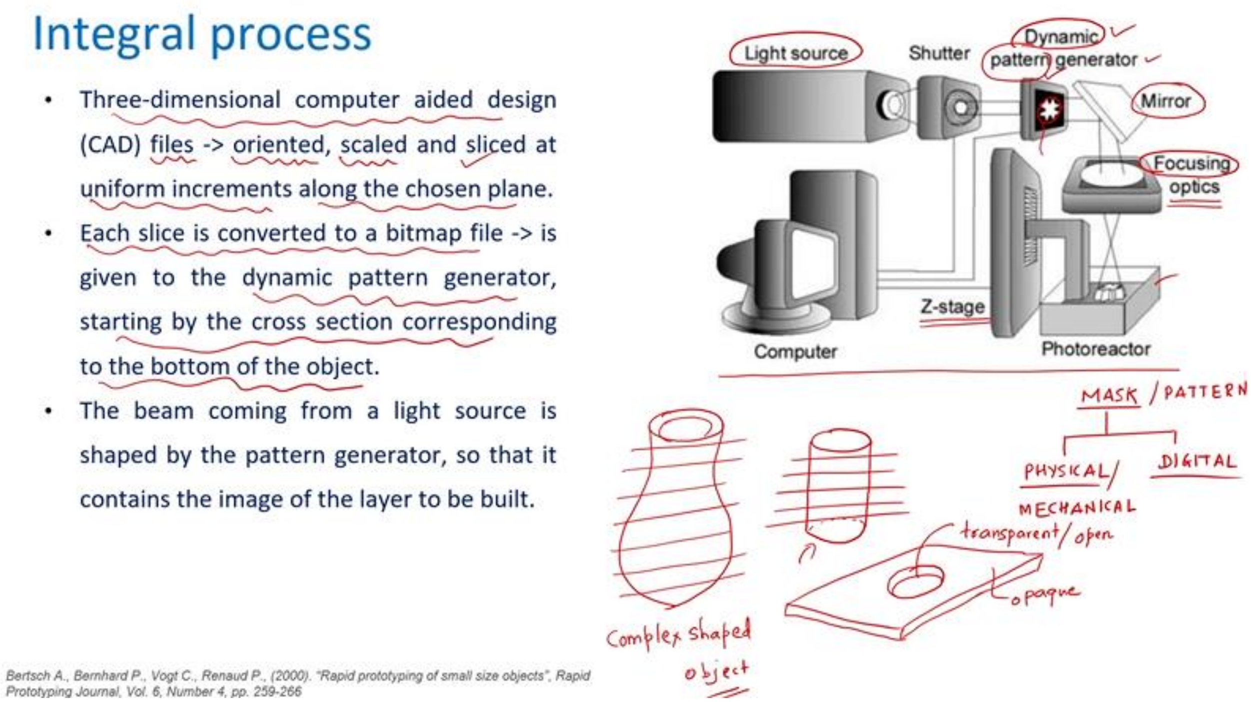


Now let us see how this integral process works. On your screen you can see the arrangement for. The integral process. Here we are having again, the substrate, or the part that to be developed. And initially it is in the form of liquid resin. And this liquid resin is kept in a container. And this container is being operated by the Z-stage. We are having light source as usual. There is a bending mirror that is also placed. We are also having the focusing optics which is helping us to get the required flux density on the surface. Now, we have seen that in the concept of integral process that the entire. 2D shape has to get polymerized. To irradiate the required surface on the resin surface, the area that to be polymerized has to be illuminated. It has to get exposed to the UV light.

So how to carry out this operation?

To carry out this operation, we are using some technique that is called as the mask technique or the pattern technique. we are using mask or the pattern. Now these masks are either physical masks or we can call them as mechanical masks, or we can have the digital masks. Now how to generate these digital masks which are dynamically getting changed. the mechanical masks are useful, or the physical masks are useful when there is a uniform cross section of the work part. consider we are having a cylinder that to be 3D printed. And this cylinder we are slicing into finite number of layers. And for every cross section we can have only one mask.

the mask is nothing but a plate. And the required portion is transparent or it is open through which we are applying the UV light energy. this is the required mass would be. this is opaque and this is transparent or open. But this is useful when the cross section is uniform as in the case of cylinder. But consider the shape that we have seen in our previous slide, if suppose the shape is very complex, suppose, the artifact of this shape has to get developed. And to manufacture such a component, where the cross section is not uniform. for such complex shape object the mechanical mass will not suffice. It will not useful. in that case we have to generate the pattern in a dynamic way.

For each and every 2D slide, the shape would be different. And for that much of portion of the slide we have to apply the laser beam energy or UV energy. So how to carry out this operation? there we are using the LCD displays. that we will see in the next slide. the dynamic pattern generator is very essential. here you notice that this portion is black, which is opaque, and this portion is open. through this particular portion, the light beam energy will get applied on the mirror and from that mirror we are getting the required light beam energy applied on the surface through focusing optic.

A shutter is being used and it is controlling the duration of application of the UV light over the substrate area. in this process of 3D printing the three-dimensional computer-aided design, CAD files are required. We are orienting them, scaling them and we are generating the sliced layers at uniform increments along the chosen plane. Each slice is converted into bitmap file. each slice which is getting generated after the slicing is converted into bitmap file and it is given to the dynamic pattern generator, starting by the cross section corresponding to bottom of the object. for every section we will be having a bitmap file. And according to that bitmap file the pattern generator is allowing the laser beam energy to pass through it. the beam coming from the light source is shaped by the pattern generator that it contains the image of the layer to be built. So, this already we have seen.

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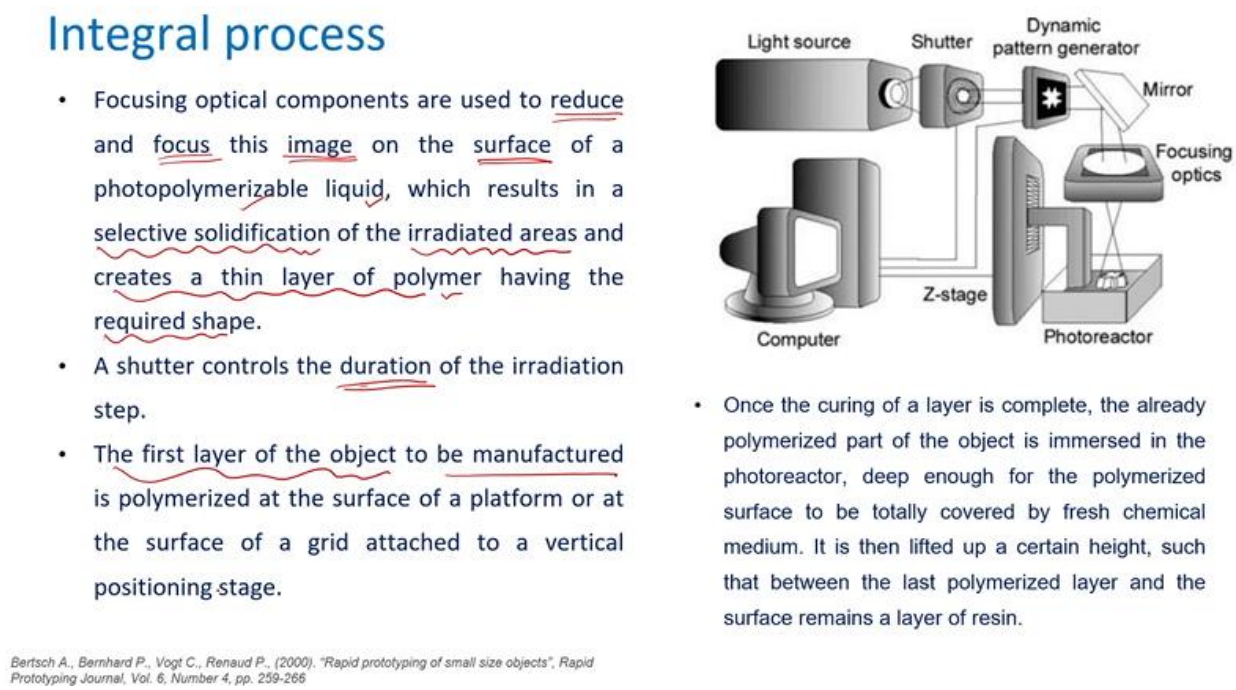


Various focusing optical components are used to reduce and to focus the bitmap image on the surface of photopolymerizable liquid, which is resulting in selective solidification. we are selecting the resin by using the bitmap image. The solidification would be done of the irradiated areas and creates a thin layer of polymer having the required shape. The shutter is controlling the duration of irradiation step. The first layer of the object to be manufactured is polymerized at the surface of a platform or at the surface of a grid attached to the vertical positioning stage. at the vertical positioning stage, at set bottom, the first layer is getting attached and over that first layer, we are building up the geometry.

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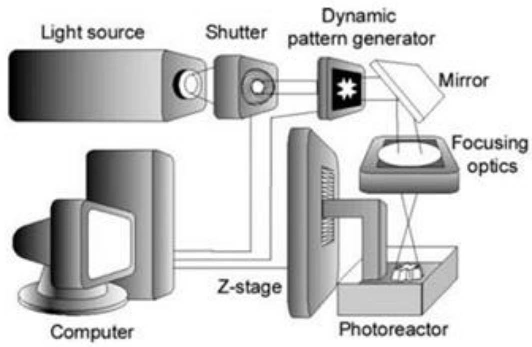
## Integral process

- The process then repeats over the same sequence of operations for the next layers, until the object is finished.
- The polymerized layers are stacked to one another by the interpenetrating polymer networks.
- When all the layers have been built, the polymerized part is taken out of the photoreactor and washed with the appropriate solvent.




Bertsch A., Bernhard P., Vogt C., Renaud P., (2000). "Rapid prototyping of small size objects", Rapid Prototyping Journal. Vol. 6. Number 4. pp. 259-266

The process of generating the pattern and then allowing the UV light to get irradiated over the liquid resin is getting repeated. And the sequence of operation would be same for the next layers as well. And it is getting repeated till we are getting the final object done. The polymerized layers are stacked to one another by the inter-penetrating polymer networks. there is a interpenetration of the layers with each other. The layers are getting stick to each other. There is a penetration of these layers and through which we are developing the 3D model. When all the layers have been built the polymerized part is taken out from the photo reactor. Then it is washed with appropriate solvent. this is the post processing that would be done after development of the 3D model. There is a washing by using appropriate solvent and then it will be utilized for the intended application.

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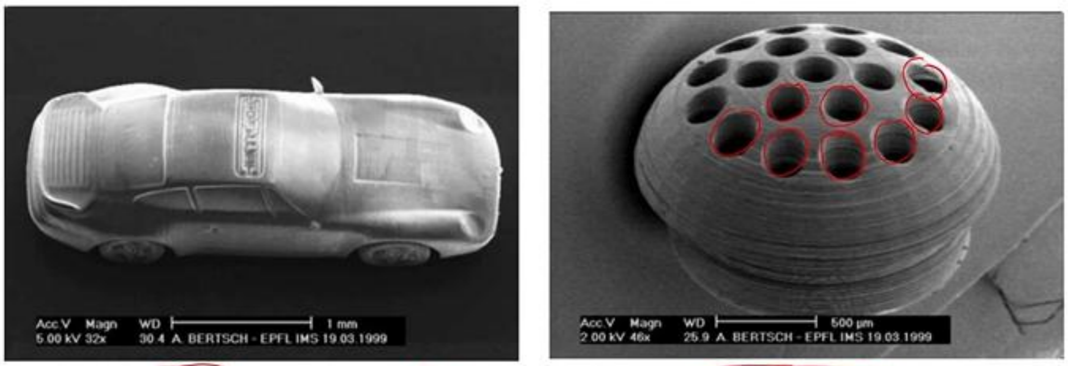


Scale model of a small car, made of 673 layers of 5 mm each μm

Part of a hearing aid

Bertsch A., Bernhard P., Vogt C., Renaud P., (2000). "Rapid prototyping of small size objects", Rapid Prototyping Journal, Vol. 6, Number 4, pp. 259-266

The some of the parts which are generated by using this integral process are there in front of you. Mostly this integral process was developed to create micro level geometries. on your screen, you can see a very small car. And it is made-up of 675 layers. And the layer size is 5 micrometers. the layer size is 5 micrometer each. And you just notice the dimensions of the car. It is in millimeters. this has been developed by using this integral process. There is another product in front of you. This is hearing aid. you can notice these are all the holes through which we are getting these sound waves and these very small hearing aid has been developed by using this integral type of 3D printing process.

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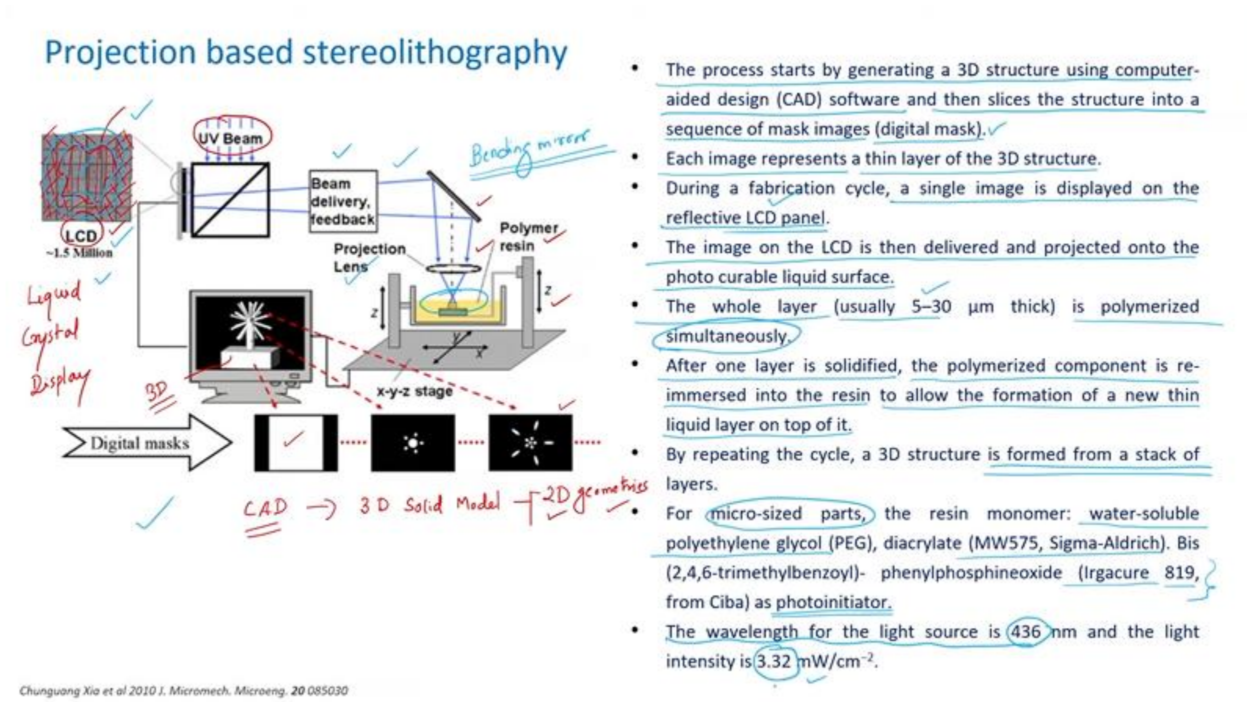


there is another interesting technique in stereolithography that is integral process itself and it is based upon the projection. on your screen you can see this particular arrangement. We are having the typical stages - the polymer resin bath, the focusing lens, and the bending mirror. Now instead of having dynamic pattern generator that we have seen in our previous case, here we are using LCD, that is liquid crystal display. you note the LCD panel is connected to the computer. And the computer is having the, CAD software. That CAD software is generating a 3D solid model into 2D models, 2D geometries. here you can see a 3D geometry. this is a 3D geometry. And at its various location, the 2D geometries which are generated can be seen. at the base, the entire portion is white. at this particular location there is a white circular shape, entity and there are white dots around it. And at the tips of that particular product we can see this kind of 2D geometry or 2D slice.

Now this information will be given to the LCD and the computer is generating various patterns and these patterns are given to the liquid crystal display. Here we are using ultraviolet beam and this ultraviolet beam is first applied over the LCD Display. And the LCD display is having the generation of that pattern. And as per the pattern on the LCD screen, the ultraviolet light is applied over the LCD. Pattern. Consider the LCD pattern is having this as the transparent or open area or this is the area that to be irradiated. The remaining area will be opaque. It will absorb the UV radiations. This portion will simply absorb the radiations. And this much of the portion is to be irradiated. So, this this will kept open and through this area, the LCD will reflect the UV light. it will just deliver the required amount of UV light from the LCD panel.

the remaining portion of the heat or remaining portion of the ultraviolet light will get absorbed. this portion is getting absorbed and this portion will get delivered through the bending mirror. I repeat here. The UV beam are applying the light on the entire LCD panel. But some portion of the LCD panel is reflecting. And whatever the portion of the LCD panel is getting reflected that much of amount of energy will be available for that particular shape, only for the polymerization. that will be carried by the beam delivery mechanism, through a set of mirrors that is a bending mirror and focusing lens. when we are getting the irradiation through this system, that much portion will get polymerized. Again, the computer now after completion of the first layer, manufacturing, the computer will send the next image to the LCD. Accordingly, the LCD will change its display.

The UV will be applied on the LCD. Certain amount of energy will get absorbed. Certain amount of energy will get transferred or it will get reflected from the portion which is designated by the CAD system, by the computer and through beam delivery system it will be applied through the application mechanism, focusing mechanism on the liquid resin. So, in this way we are developing the 3D model by using this projection based stereolithography. The projection will be carried out by using the LCD and the CAD based technique. this process starts by generating a 3D structure using computer-aided design software, and then we are doing the slicing the structure into a sequence of mask images. these mask images are called as digital mask. each image represents a thin layer of the 3D structure.

during the fabrication cycle, a single image is displayed on the reflective LCD panel. as we have seen that this is the reflective LCD panel. The image on the LCD panel is delivered and projected on the photo-curable liquid surface here.  this is the photocurable liquid surface. The whole layer, usually which is having the thickness of about 5 to 30 Micron, is polymerized simultaneously. the entire layer is getting polymerized, simultaneously. After one layer is solidified, the polymerized component is re-immersed into the resin to allow the formation of new thin liquid layer on top of it.  once one layer is getting solidified/polymerized then the stage will move in a downward direction. The liquid will flow over that polymerized layer and then the next layer will be processed.

By repeating this cycle, a 3D structure is formed from a stack of layers. to generate micro size parts, various monomers are used such as water-soluble PEG, polyethylene glycol, diacrylate (MW575, Sigma-Aldrich) and trimethyl benzoyl, then phenyl phosphine oxide. It is also popularly called as Irgacure 819, and these materials are considered as the photo initiators. The wavelength of the light source is taken as 436 nanometer and the light intensity or the energy intensity is in the order of milliwatt, and that is about 3.32 milliwatts per centimeter square.

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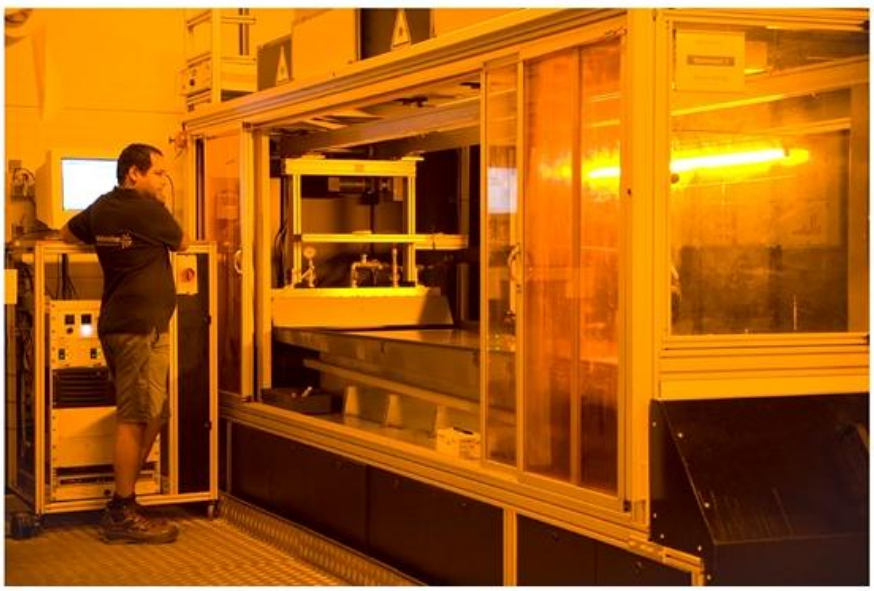

Figure. Mammoth Stereolithography system

Commons.wikimedia.org. 2022. File:Mammoth Stereolithography.jpg - Wikimedia Commons. [online] Available at: <https://commons.wikimedia.org/wiki/File:Mammoth_Stereolithography.jpg> [Accessed 15 September 2022].

**Benefits of stereolithography**

- Cost effective
- Excellent surface finish
- Repeatability

**SLA 3D printing is primarily used for**

- Parts requiring high accuracy and features as small as 0.07 mm
- Good surface quality for cosmetic prototypes
- Form and fit testing

So, this is an interesting way to create the 3D models, and in particular the projection based stereolithography is used for generation of micro components. Well, in the industry we require to manufacture meso-level or macro level of components. One such mammoth 3D printing machine is there on your screen. this is a stereolithography based system. You can notice its scope in terms of the size of the components it can handle. Certainly, the scope is in meters. Now let us look at the benefits of the stereolithography. This system is cost effective, certainly. It is producing excellent surface finish and the repeatability is very high.

due to this the laser-based scanning process is popularly used. We can even manufacture parts of very small size, say 0.07 mm. It is very small; 70 microns part size can easily be manufactured which we have already seen by using projection-based techniques. Good surface quality is achieved. For development of cosmetic prototypes, when we want to realize the design at early stage, we have to generate the prototypes and their surface quality is in acceptable range. Generally, the SLA 3D printed objects are used for testing the form and fit of the objects. So as I mentioned in the previous class as well, in rapid prototyping we have realize the form and feet of various parts of an assembly at the stage of its manufacturing itself. there, these types of techniques or this stereolithography is helping a lot to create the parts. We can assemble them together and then judge whether our design is proper or not?

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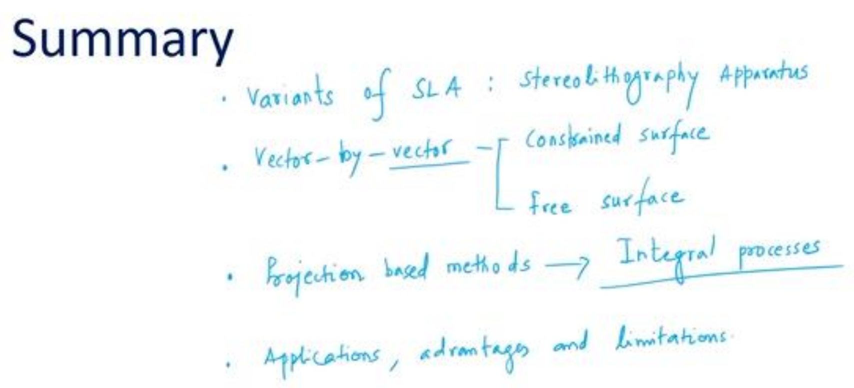


With this, I would like to summarize for today's class. So, in this class, we have seen various variants of SLA, stereolithography apparatus. And these variants we have seen that is, the vector by vector method variant. Here as well, we have seen the constraints surface-based system and free surface-based system. After that we have seen in a comprehensive way, the projection-based methods. And these are in general, called as integral processes. we have seen their applications and the advantages and limitations in short, applications, advantages, and limitations. fine! With this we stop for this class. In the next lecture, we will see the SLS that is selective laser sintering in detail. till then, goodbye. Thank you for watching this lecture. Bye!