Aalto University

Zain Ul Ihsan

Projection Microstereolithography Apparatus

A Master's Thesis

Espoo, September 05, 2016

Thesis Supervisor (Politecnico di Torino): Prof. Chiaraviglio Alessandro

Thesis Supervisor (Aalto University): Prof. Jouni Partanen

Thesis Advisor (Aalto University): Pekka Lehtinen

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School of Engineering

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To my Parents, without the support, drive and inspiration that they have given me, I might not be the person I am today.

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Author Zain Ul Ihsan

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Abstract

Additive manufacturing (AM) is the dawn of new industrial revolution. It has a potential to revolutionize the way we make everything. Stereolithography (SL) is a rapid prototyping (RP) and manufacturing technology that enables the generation of physical objects directly from the CAD data files. In SL the products are fabricated layer-by-layer by curing the liquid resin. Microstereolithography (μSL) allows the fabrication of 3D parts with μm accuracy, including the re-entrant and curvilinear microstructures that are impossible to make by using conventional micromachining.

In this thesis, a digital micromirror device (DMD) based Projection microstereolithograply (PμSL) setup has been built. Three different coatings for resin vat and three different resins have been tested for the fabrication purposes. Similar to Projection stereolithography (PSL), in PμSL, an entire layer is manufactured by irradiating its whole surface only once instead of scanning the layer cross-section. In the built setup, an UV LED is used as a light source and there is only one mobile element, the z translator, while all the other equipment is fixed.

Keywords Additive Manufacturing, Rapid Prototyping, Stereolithography, Microstereolithography.

Preface

This master thesis is written at Aalto university (Finland) in the Micronova research centre and is handed to Politecnico di Torino (Italy) based on Erasmus exchange program.

I would like to thank Aalto university, especially the Micronova research centre, for providing me a profound environment for study and all of the equipment needed for the research. I would like to express my deep gratitude to my supervisor Prof. Jouni Partanen for introducing me to the world of additive manufacturing and for his invaluable support throughout the project. I would also like to thank Prof. Chiaraviglio Alessandro for believing in me and providing me consistent encouragement and support. Last but not least, I would like to thank my advisor, doctoral candidate Pekka Lehtinen and doctoral candidate Verho Tuukka, for their worthy guidance and patience they provided me during the entire project and I really appreciate their ever-ready helping attitude.

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Abbreviations

2D	Two Dimensional
3D	Three Dimensional
μSL	Microstereolithography
AM	Additive Manufacturing
CAD	Computer Aided Design
CLIP	Continuous Liquid Interface Production
DLP	Digital Light Processing
DMD	Digital Micro-mirror Device
GUI	Graphical User Interface
HDMI	High Definition Multimedia Interface
LCD	Liquid Crystal Display
LOM	Laminated Object Manufacturing
MIP-SL	Mask Image Projection based Stereolithography
PDMS	Polydimethylsiloxane
PI	Photoinitiater
PμSL	Projection Microstereolithography
PμSLA	Projection Microstereolithography Apparatus
PSL	Projection Stereolithography
RP	Rapid Prototyping
SL	Stereolithography
SLA	Stereolithography Apparatus
SLM	Spatial Light Modulator
SLS	Selective Laser Sintering
STL	Stereolithography CAD Software file format created by 3D System
UV	Ultraviolet

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1 Introduction

1.1 Background

The development of Nano and Micro manufacturing technologies is growing rapidly in the industrial area due to which a tremendous increase of investment in this field has been seen in the past decade.[8] Nowadays, a diverse range of Nano and Micro manufacturing technologies are being utilized with the aim of innovations in human interfaces, health care, environmental, energy and aerospace engineering. To manufacture precise models in Nano and micro manufacturing, Stereolithography (SL), one of the technique among Rapid Prototyping (RP), plays a great role.

Rapid Prototyping, developed in 1980s, is the first ever technology of creating layer by layer a 3D object using Computer-Aided Design (CAD) and these days it is one of the fastest growing and most talked about manufacturing technologies on this planet. It is providing diverse opportunities for new product design and manufacturing. Nowadays, terms Additive manufacturing (AM) and 3D printing are mostly used instead of Rapid Prototyping.[1,2]

All of the AM technologies manufactures a working prototype or model by fabricating it layer by layer using CAD system. But these technologies varies according to the material used and part building techniques, which defines the strength and fabrication accuracy of the final product and cost of the AM equipment. Strength is generally related to the material used for part production while the fabrication accuracy depends on the fabrication technique of the AM equipment. Mainly, liquid photopolymers are used for Stereolithography (SL) processes and plastics are used for other processes while, some techniques also involves metals and ceramics for production. For instance, metal or ceramic powder is used in Selective Laser Sintering (SLS) and metal sheets are used in Laminated Object Manufacturing (LOM).[3]

Photopolymers were developed in late 1960s and soon became broadly used in several commercial areas, while in the mid-1980s, they were applied to fabricate a solid 3D part and that's how SL technology came into existence. Stereolithography is one of the most popular and successful AM process. In this process, a liquid photosensitive polymer (also known as resin) is cured or solidified by scanning of a UV light source across its surface. The light source supplies energy that induces a chemical reaction in liquid photopolymer which leads to the bonding of large number of small molecules and forming of a highly cross linked polymer. SL parts are widely used rather than parts from other manufacturing technologies because of their high accuracy, surface finish and moderate mechanical properties.[5,7]

The entire SL process to create a 3D part consist of input data, part preparation, layer preparation and finally formation and stacking of 2D cross sectional slices. Three approaches have been configured so far for the photopolymerization processes including, Vector scan, Mask projection and Two-photon polymerization approach. In Vector scan based SL process, the layer or cross section is cured by scanning a laser beam over the surface of resin while, in Mask image projection based Stereolithography (MIP-SL) process, the entire cross section is cured at one time by using dynamic mask generator, such as, Liquid Crystal Display (LCD) screen or Digital Micro-mirror Device (DMD).[7] MIP-SL is relatively faster and easy operable than vector scan approach, as, an entire part cross section can be cure at one time, rather than scanning a laser beam and also it is cheaper than vector scan based SL process, as, the entire laser and scanner system can be replaced by dynamic mask generator.[9]

While, two photo polymerization is a microfabrication technique and in this technique, the part is manufactured directly inside the reactive medium rather than on its surface. Microstereolithography (µSL) works on the same manufacturing principle of SL, but the resolution of µSL is much better than SL and other rapid prototyping techniques. By using µSL, one can even fabricate the objects having the details of few micrometers in three direction of space. µSL has been successfully used to produce the components for micro-robotic, micro-fluidic, Microsystems and biomedical applications.[6]

In projection microstereolithography (PµSL), similar to mask projection SL, an image created or reflected by dynamic mask is projected on the surface of the photosensitive resin, after passing through series of optical components, in order to cure the 2D slices section. PµSL systems usually vary according to the choice of the dynamic mask. Generally, liquid crystal display (LCD), digital micromirror device (DMD) and spatial light modulator (SLM) are used as a dynamic mask generator. By using PµSL technique, besides fast fabrication speed, unwanted thermal polymerization can also be avoided.[6]

1.2 Research objective

The objective of the thesis is to build a projection microstereolithography device for the fabrication of 3D microstructures by following the principle that the solid microstructures should be able to produce by focused light, which is projected over the surface of photo-curable resin and undergoes a photopolymerization process to fabricate the desired solid microstructures. The PµSLA constructed in the research work is based on bottom up orientation approach and consists of a LED source, a DMD, various optical components, a transparent resin vat, a platform and an elevation device connected with a computer.

In order to obtain the micrometer resolution, the lateral dimension of each pixel projected on the bottom surface of resin vat should be in the range of few micrometers. Since, the bottom up oriented approach has been used for the construction of built setup, so, different coating materials have been tested so that the bottom surface of resin vat should be non-sticky and the cured layer does not get attached to it. Besides this, in order to achieve good fabrication accuracy some different resins have also been tested.

The setup is built using commercially available and self-made components aiming to keep the cost at its minimum level. The current price of the system is between 2000 € - 3000 €, but with the optimization of some components the price can be even more reduced. The inexpensiveness of the setup makes the technology more available to other researchers and organizations, which may lead to new innovations.

2 Additive Manufacturing

2.1 Introduction

Since, 20 century humans/engineers are trying to improve the manufacturability of the products. With the increase in the demand of customization and uniqueness among the customers, traditional mass production and manufacturing process are not so efficient. Now the production is done in small batches with high degree of the customization, thus, creating a high value product.

Rapid Prototyping (RP) is a family of production techniques, which are used to fabricate engineering prototypes based on computer aided design (CAD) model of the item, in minimum possible lead times. The traditional method of production i.e. machining, requires significant lead times up to several weeks and sometimes even longer depending on complexity of the product, difficulty in ordering materials and scheduling of production equipment.[10] But RP, emphasis on creating a quick output i.e. a prototype or basis model from which the final product can be obtained.[7]

Nowadays, instead of prototypes, many parts can be directly manufactured by this technology. Due to the recent advancement in the field of RP, the users have realized, the term “RP”, does not describes the new applications of this technology accurately. Moreover, the basic principal of these technologies i.e., fabrication in additive manner is also ignored by the term RP, so there is a need to redefine the term. While it is still under debate, but recently adopted ASTM agreement standards uses the term Additive Manufacturing (AM), instead of RP.[7]

Additive manufacturing allows parts that were once thought impossible, can be created by layer by layer approach. It gives a whole new dimension to the manufacturing methods, since we no longer needed to think about the machining, thus, giving the product designer whole new degree of freedom to construct their products.

The basic principle of AM technology is that the part can be directly fabricated in an additive manner from the model without any process planning. It uses information from a computer aided design (CAD) and then, converts the file into machine readable format, usually stereolithography (STL) file. Once the product is designed and developed in the CAD software. The software then analyses the model while converting it into STL format, taking a series of cross-section and working out the distribution of space and solid matter within each layer. Once, the STL is been generated, the data is sent to the 3D printing machine where it starts manufacturing it by depositing it layer by layer.[1]

2.2 Fundamentals of Additive Manufacturing

The generic AM process involves number of steps in order to get a complete physical resultant part from the virtual CAD description. A brief overview of these steps is illustrated in figure 2.1.[7]

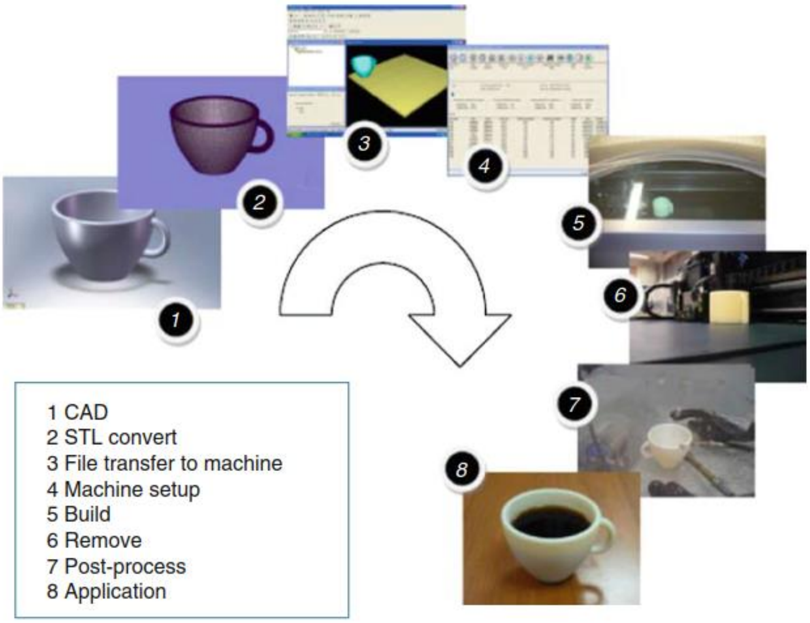


Figure 2.1 Generic Additive Manufacturing process.[7]

2.2.1 CAD creation

All models that are required to be 3D printed must be designed and modeled in a suitable CAD software either in the form of 3D solid or surfaces. To obtain the CAD file of an existing product, reverse engineering i.e. laser scanning can also be used.

2.2.2 STL conversion

All CAD (solidworks, catia, etc.) files needs to be converted into STL file which is kind of standard for additive manufacturing machines. The STL file takes external closed surfaces and divides into layers depending on the system configuration.

2.2.3 Data transfer to AM machine and STL file manipulation

Once, the STL file has been generated. The data is transferred to the machine with required setup properties. In this step, size, orientation and position is determined.

2.2.4 Machine setup

Before building the desired part, AM machine must properly adjusted in order to get the good result, i.e., build parameters like, energy source, material constraints, layer thickness must be properly adjusted.

2.2.5 Building of part

Building of desired part mainly depends on pre-adjusted machine parameters. It is an automated process which does not require any supervision, but to be on safe side, superficial monitoring of machine is required to ensure that no errors have taken place during the production.

2.2.6 Removal

Once the manufacturing is done, part must be safely removed from the AM machine. In order to avoid any accident or damage to the manufactured part, one must have to take the safety measurements while removing the part, i.e. the operating temperature should be sufficiently low or there should not be any actively moving part, etc.

2.2.7 Post processing

Once the parts are removed from the machine, some parts may require some additional post processing before they are acceptable for use. They may contain some supporting features that must be removed or they may be weak at this stage. So, in some cases, a careful, time consuming experienced manual or machine manipulation is also required.

2.3 Advantages, Drawbacks and Challenges of AM technology

Additive manufacturing offers a lot of benefits when compared to traditional machining and manufacturing process e.g. simplification of supply chain, decreased lead times freedom of design and improved quality of prototyping, etc. These benefits naturally outweighs the costs associated with the additive manufacturing, but even though over the years, with increased computational powers and quality of softwares the cost has actually reduced and it has been observed that there is an average savings of 80% both in time and cost over the traditional subtractive production methods.[31]

Generally, it has been noted that when using additive manufacturing for metal products, material wastages decreases by 40%. Also, product developed using additive manufacturing doesn't require any tools, dies and punches which makes this process economically feasible. Even there is no need to for additional storage space for spare parts, as, additional or spare parts can be made as required.[31]

However, AM technology also faces certain challenges, which have restricted its use in certain application areas. For instance, nonlinear behavior of AM fabricated parts restricts it use in the production of high strength parts, as, AM manufactured parts have different strength in different directions in comparison to conventionally manufactured parts. They exhibits high strength in lateral direction as compared to build up direction. Stair- stepping phenomenon is also an issue, but this phenomenon is only common in projection based AM systems. As in this case, the slicing layers are rectangular in cross-section so, they cannot reconcile with the curved surfaces which affects the surface quality and roughness of produced parts.[31]

The main existing challenge in the field of AM is the direct manufacturing of the metal parts, since, processing of metal parts directly built from AM technology is still uncommon comparing to indirect methods of AM technology, so AM technology should be extended to fabricate metal parts with acceptable accuracy and strength. Also, the existing AM systems are only polymers, paper and ceramics based so, there are still many materials that require attention for fabrication purposes such as, copper, magnesium, etc. Lastly, due to high manufacturing cost and availability of less number of potential users, AM systems are quiet expensive. This kind of situation occurs in the beginning stage of any new technology. But recently, some low cost AM have been introduced in the market for personal use and a high-volume sales of these system has been noticed.[31]

2.4 Future of AM

AM is progressing rapidly every day. It has revolutionized the "Design to Manufacturing" process and it is changing the future of product development and manufacturing. The overall cost of AM is going to go down further in the next ten years as many of the patents are going to expire which will create an opportunity in the market for new 3D printers. The products made using this technology takes time but this will be greatly reduced as the researchers are trying to make faster 3D printers.[31]

In future, additive manufacturing will be quite common in aerospace, automotive, artistic, architectural and medical industry. Research has been carried out to fabricate the part using direct metals such as titanium which can be used in aerospace applications which will reduce the manufacturing cost by 30 - 35% for low volume service parts. Furthermore, AM has already shown its potential in the medical sector and even researchers are trying to involve the AM in tissue engineering in order to create biochemical parts such as scaffolds for the restoration of tissues.[31]

3 Stereolithography

Stereolithography is one of the most popular and widely used AM process, which works on the basic principle of photopolymerization. This technology generates a part or prototype by curing a liquid photosensitive polymer, also known as resin, by using an irradiation light source. The irradiation light source supplies the energy which basically induces a curing reaction. The solidification or curing reaction, which occurs in stereolithography resins is an exothermic polymerization process which is distinguished by chemical cross-linking reactions. The curing reaction is initiated by introducing a proper amount and form of energy, which depends on selected stereolithography technique. As a result of curing reaction, an insoluble, infusible and highly cross-linked 3D network is formed. Figure 3.1 demonstrates the different techniques to induce a curing reaction in sterolithographic processes.[2,4]

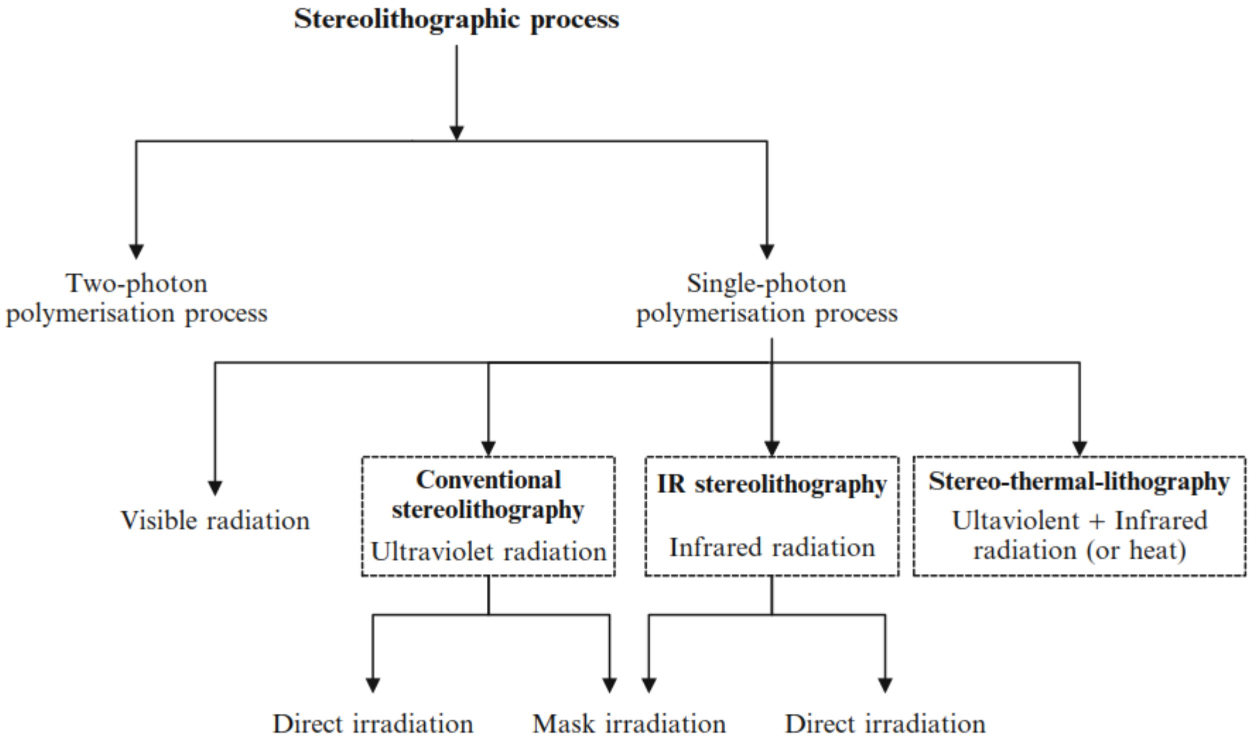


Figure 3.1 Different techniques to induce the curing reaction in stereolithographic processes.[4]

3.1 Photopolymerization

When an electromagnetic radiation of suitable wavelength interacts with monomers or polymer molecules, it induces formation and breakdown of chemical bonds. The process of reacting molecules of small molar mass and short chain length (monomer) together in a chemical reaction to form longer chains of polymers or three-dimensional networks with greater molar mass is called polymerization. Practically, the term photopolymerization emphasis on polymerization process initiated by visible or ultraviolet light. Whereas, theoretically, the polymerization process can also be initiated by other wavelengths of electromagnetic radiation.[11,14]

The photopolymerization reaction mechanism can be described in four phases: initiation, association, propagation and termination, presented in Eqs. (1 - 4). Photopolymerization in a photosensitive material is activated by small molecules known as, photoinitiators (PIs), which basically absorbs light of specific wavelength. In the first phase, one or more radicals (R^*) are formed by excitation of PI molecules due to the absorption of photon. Then in the association phase, these radicals induces the conversion of monomer species (M) in growing polymers (P^*), which continues to elongate by addition of monomer units representing the propagation phase. The elongation is terminated when two growing chains interact and meet at their radical ends.[11,14]

Initiation	$PI \xrightarrow{\lambda} PI^* \longrightarrow R^*$	***Eq. 1***
Association	$R^* + M \xrightarrow{k_1} P^*$	***Eq. 2***
Propagation	$P_n^* + M \xrightarrow{k_p} P_{n+1}^*$	***Eq. 3***
Termination	$P_n^* + P_m^* \xrightarrow{k_t} P_{n+m}$	***Eq. 4***

In the above mentioned equations, "λ" represents the absorbed energy and "k" with the subscripts shows the reaction rate constants for each conversion reaction. The general representation of photopolymerization process is shown in the figure 3.2.[12]

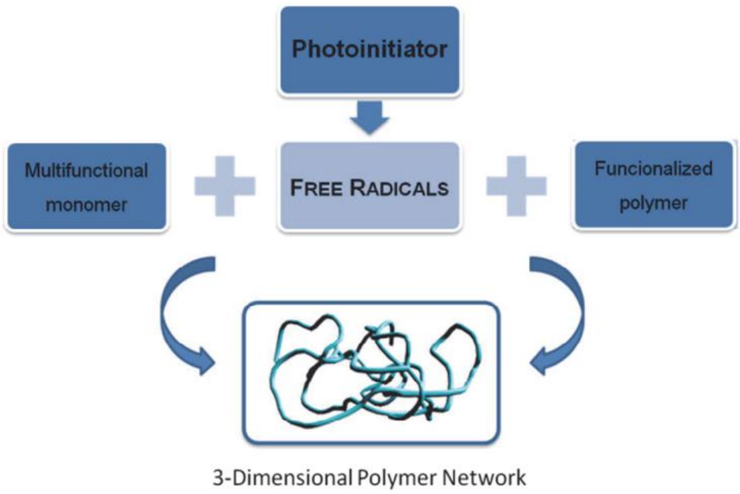


Figure 3.2 A representation of photopolymerization process.[12]

Instead of radical photopolymerization, photoinitiation can also be classified by cationic and hydrogen abstraction polymerization. In cationic polymerization, the polymerization process is initiated by reaction between acidic species and monomers. Where, a positively charged carbon atom (carbocation) is formed in the initiation process and acidic species are produced when the cationic photoinitiator is affected by light. While, in hydrogen abstraction, the photopolymerization is initiated by H-donor radical. The H-donor radical is formed by abstraction of hydrogen molecule by photoinitiator, generating a donor and a ketyl radical. Ketyl radical basically links with the growing macromolecular chains.[14]

3.2 Photopolymerization v/s Photocrosslinking

The term "photopolymerization" describes the forming of polymer structure having longer chains and greater molar mass from the molecules of small molar mass and short chain length. While in "photocrosslinking", the covalent bond is formed between oligomers (already polymerized molecular chains) by opening of double bond which hysterically increases the materials viscosity and turns it into solid. The difference between the photocrosslinking and photopolymerization lies in the details of the photocrosslinking mechanism. Contrary to photopolymerization, photocrosslinking involves the absorption of a photon in every chain propagation step, while, only the initiation phase is light dependent in photopolymerization.[11,13,14]

3.3 Photopolymers

Photopolymers are polymer materials sensitive to light, as, they change their properties and state from water like liquid substance to solid plastic like substance, when they are exposed to light. Usually, they are kept in liquid state for general use but they are also present in the form of sheets. Commercial photopolymers can be cured by various type of radiations, including electron beams, X-rays, gamma rays, UV and in some case also with visible light. Photopolymers are quiet eco-friendly and they can work without any volatile solvent in most of the industrial processes, due to which, they were quiet popular in recent history and even very common in our daily lives. They can be observed in different sort of coatings in metal, paper, wood and plastic materials. They are also used in dentistry for filling deep groves to prevent cavities. Some common photopolymers are epoxies, acrylics, polyvinyl cinnamate, polyamide (PA), polyisoprene, polyimidies etc.[15]

3.3.1 Composition of Photopolymers

Photopolymers are basically consists of several components including binders, chemical agents, photoinitiators, additives, colorants and plasticizers but there three main components which build the photopolymers. Named as,

- Oligomers
- Monomers
- Photoinitiators

Oligomers are also called binders, basically they are molecules of reactive intermediate molecular weight consisting of few monomers. Generally, photopolymers consists of 50-80% of oligomers. Where, monomers are chemically bonded small molecules which interacts with other monomers or oligomers in repeated fashion way to form new polymers. Photoinitiators are most important constituent of photopolymers as, they convert light energy into chemical energy by forming free radical or cations. They breaks into two or more particles on the interaction of UV light and react with oilgomers and monomers and bind them together. Photoinitiators are very sensitive to specific wavelength of light source. Some common examples of oligomers, monomers and photoinitiators are given in the list on next page.[15]

Table 3.1 Common constituents of Photopolymers.[15]

Oligomers	***Monomers***	***Photoinitiators***
A-Methyl Styrene-Dimer	Methacrylic acid	Isopropylthioxanthone
A-Methyl Styrene-Tetramer	Isodecyl acrylate	Benyophenone
Acrylic Acid Oligomers	Acrylic acid	2,2-azobisisobutyronitrile
Methyl Methacrylate Oligomers	Trimethylpropane trimethacrylate	Diaryliodonium salts (cationic)
Vinyl Alcohol Trimer	N-Vinyl pyrrolidone	Triarylsulfonium salts (catinoic)

Along with photoinitiators, neutral absorbers can also be used in the photopolymers, in order to absorb photons. Neutral absorbers are quiet efficient in reducing the polymerized thickness during curing process as, the absorbs the light and dissipates the captured energy without intruding the polymerization process.[6,14]
The effect of utilization of neutral absorber is described in more detail in the next chapter 4.

3.4 Photopolymers and Stereolithography

Photopolymers were developed in the late 1960s and instantly started to broadly applied in several commercial sector mainly in printing and coating industry. Initially, the curing of photopolymers was done without any pattering but in the mid-1980s, while experimenting with UV curable materials, Charles (Chuck) discovered that solid polymer patterns could be produced and he could build a solid 3D part by curing one layer over the previous layer. That is how SL technology came into existence and shortly thereafter, the company "3D Systems" launched their SL machines to the product development industry. Commercial photopolymers can be cured by various type of radiations, including electron beams, X-rays, gamma rays, UV and in some case also with visible light, but mostly, UV and visible light radiations are used for curing purposes in SL systems.[7]

Nowadays, SL is one of the most popular and widely used AM process, commercialized by 3D Systems Inc. in 1987, due to its rapidness, accuracy and versatility in manufacturing parts on different geometric scale. SL system generates a 3D part by using light to selectively solidifying the photosensitive resins. There basically two different approaches to fabricate a 3D model in conventional SL method, which are described later in detail but, the entire process of generating a model by using stereolithography apparatus (SLA) comprises of following steps:[5]

1. Creation of model on CAD system
2. Exportation of CAD model into STL file
3. Addition of support structure (If required)
4. Specification of build style variables and parameters, which are necessary for slicing
5. Slicing of computer model to generate the information that controls the SLA
6. Building of 3D part using sliced file
7. Post processing

8. Post curing (If required)

A general flowchart SL building process is demonstrated in the figure 3.3.

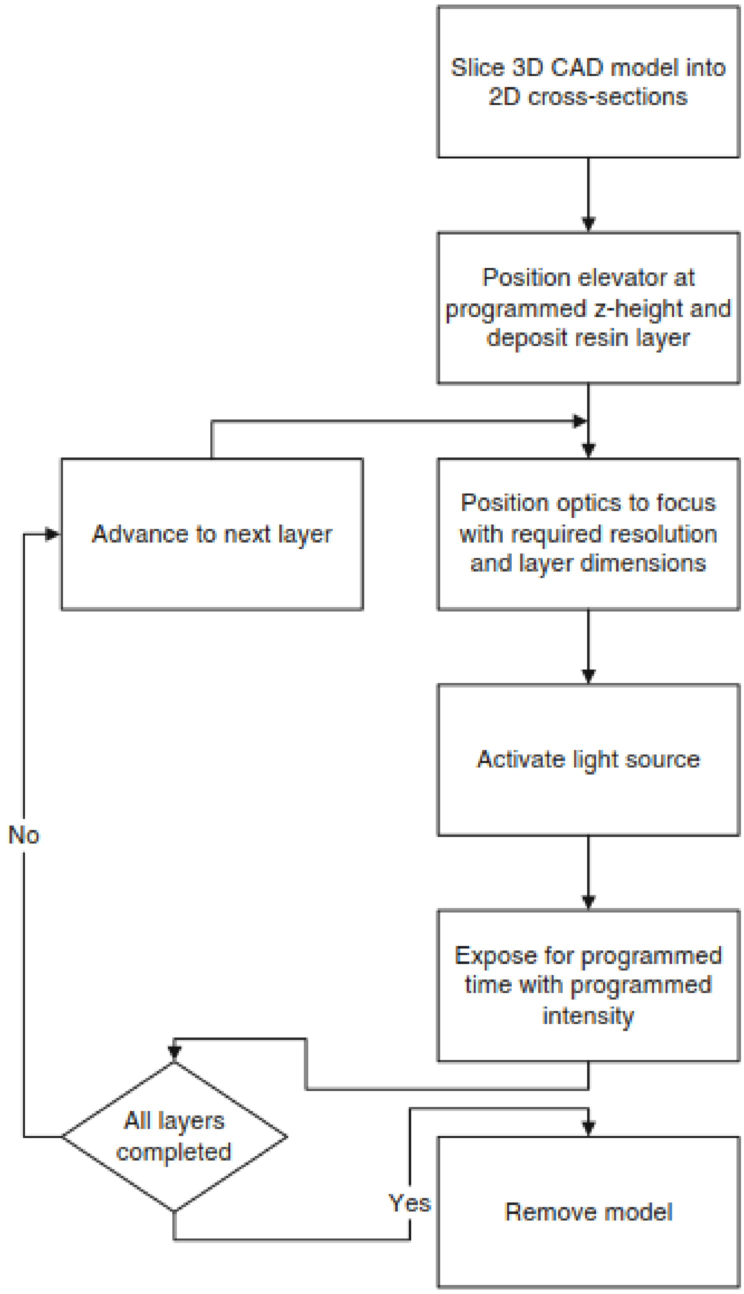


Figure 3.3 Flowchart of SL building process.[5]

3.5 Conventional Stereolithography Configurations

Conventional SL is a single-photon photo-fabrication process that generates the model by selectively solidifying the photosensitive resin by using the UV light. There are two basic approaches for conventional SL processes, named as,[4,7]

1. Vector scan or point-wise SL process
2. Mask projection or layer-wise SL process

The main difference between both of the process is only the curing method of each layer but rest of the procedure is almost same.

3.5.1 Vector scan or point-wise SL process

Just like many other AM processes, in vector scan or point-wise SL process, the part is built by fabricating cross-sectional contours or slices, one on the top of previous slice or layer. These layers are created by tracing 2D contours of a CAD model with a laser, in a vat of photopolymer resin. The building part rests on the platform, which is dipped into the resin vat. After the creation of a layer, platform is leaving a thin film from which the next layer is formed and then the laser starts tracing the next layer or slice of the CAD model and thus the final part is achieved. In this process, making of a fine spot of laser plays a key role, which is controlled by using galvano-mirror or X-Y stage. A schematic of vector scan based stereolithography apparatus (SLA) is shown figure 3.4.[7]

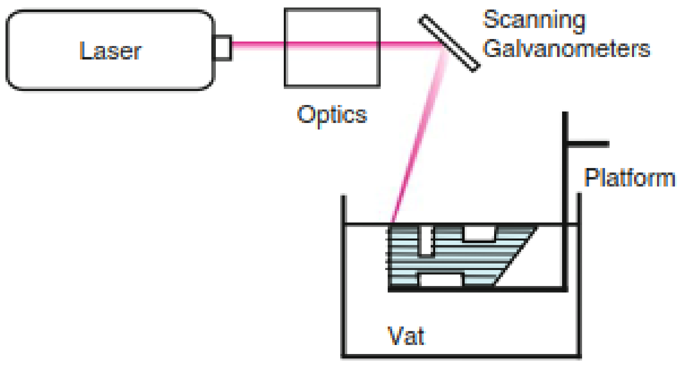


Figure 3.4 A Schematic of vector scan or point-wise SLA.[7]

3.5.2 Mask Projection or layer-wise SL process

In Mask projection or layer-wise SL process, the part is manufactured by shining a flood lamp through a mask. In this process, the exposure energy cures the entire cross section of the 3D physical object. Generally, liquid crystal display (LCD), digital micromirror device (DMD) or a digital processing projection systems are used for the generation of masks. Contrary to point-wise scan process, layer-wise scan process gives rise to discretization phenomenon, in which a stack of layer causes stair steps on slanted or curved surface, so post processing is required after the part generation. The projection method in SL are also known as mask image projection based stereolithography (MIP-SL) or as projection stereolithography (PSL). A schematic of mask projection based SLA is shown in figure 3.5.[4,7]

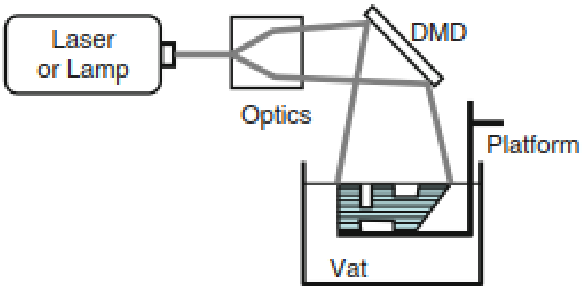


Figure 3.5 A schematic of mask projection based SLA.[7]

3.6 Different approaches for Projection Stereolithography

The PSL apparatus can be oriented in three different ways according to movement of z-axis. Which are,[16]

1. Top down orientation approach
2. Bottom up orientation approach
3. Side wise orientation approach

3.6.1 Top down orientation approach

Top down projection approach is also known as free surface technique because in this technique, the resin is cured at resin surface, since the light is exposed from above. In this technique, it is very difficult to control the layer thickness as it depends on gravity, viscosity and surface tension of the resin and it also varies if the top part of cured object near to free surface has complex or different geometry than bottom cured part. The layer thickness can be controlled by using a low viscosity resin or by using a sweeping blade which smoothen the resin surface but sweeping blade may reduce the building speed, since it takes a lot of time to smooth every new fresh layer of the resin.[14] A general schematic of top down orientation approach is shown in the figure 3.6.

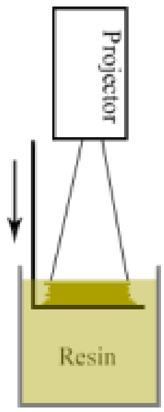


Figure 3.6 A schematic for top down orientation approach.[16]

Besides smoothing of resin surface, oxygen inhibition is also an issue which must be controlled while building a part. Since, the fresh layer of resin is always in contact with the air, so the outermost layer of cured object will not be cured completely due to the presence of oxygen. Oxygen inhibition and also the smoothing of fresh resin layer can be controlled by putting a transparent glass window onto the resin surface so that the curing occurs through the transparent glass window but this gives rise to another problem which is, cured layer may stick to the glass.[6,14]

3.6.2 Bottom up orientation approach

Another most commonly approach used in PSL is bottom up orientation approach. In this technique, the mask image is projected from the bottom of the tank, so the bottom of the tan must be transparent. The layer thickness is not a major issue in this case since, it is accurately controlled by computer program by leaving a small gap between bottom surface of the resin tank and the platform. Contrary to the top down orientation approach, once the layer is cured the platform is moved in upward direction. There is also an obstacle in bottom up orientation approach that cured layer may stick to the bottom of the resin vat which may stops the curing process. So, in order to avoid this, the sticking force between the cured part and platform should be greater than the force between the bottom of the resin vat and the cured part. This can be overcome by coating a resin vat with some non-sticky material or by detaching the cured layer by slightly tilting the resin vat to decrease the pulling force.[14,17] A general schematic of bottom up orientation approach is shown in the figure 3.7.

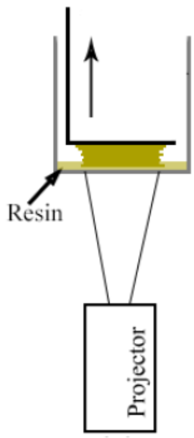


Figure 3.7 A schematic for bottom up orientation approach.[16]

Bottom up orientation approach has several advantages over top down orientation approach. Firstly, as the part height is independent of container depth, so a shallow vat can be used, which reduces the required volume of liquid resin. Secondly, as the liquid resin is not in the contact with the oxygen rich environment so, the oxygen inhibition is not a problem in this case. Thirdly, the layer thickness can be controlled by the motorized translational stage, so, the resin viscosity, surface tension and gravity has no effect on the layer thickness and there is no need for using the sweeping blade, which also increases the build speed.[14,17]

3.6.3 Horizontal Side-wise orientation approach

This horizontal side-wise PSL orientation approach is not very traditional. In this orientation, the projector is set to project the mask image through the side of the resin container. Just like top down orientation approach, the projection platform is inside the container but against the sidewall and the platform is moved horizontally as the layers are cured. Just like bottom up orientation approach, the sides of the container wall should be transparent and should be coated with some non-sticky material to avoid the sticking problem. The major benefit of using the horizontal side-wise orientation approach is that it gives stability of setup. As, it gives larger area to stand on with a lot lower centre of mass, whereas, the previously mentioned approaches have smaller area to stand on with relatively high centre of mass, which makes them unstable. A general schematic of horizontal side-wise orientation approach is shown in the figure 3.8.[16]

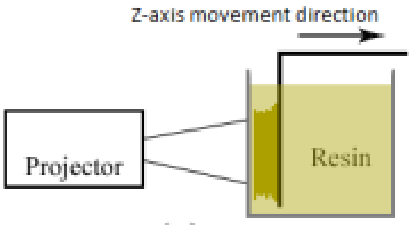


Figure 3.8 A schematic of horizontal side-wise orientation approach.[16]

3.7 Limitations in Stereolithography

SL is quiet popular and successful AM technique but there are still some complexities and limitations which need to be overcome. Among them, shrinkage is the most important problem, which is the logically aftereffect of polymerization process in which small molecules forms large molecules, resulting in increase of density. Curl distortion during curing process is also an issue which must be taken control of. Besides curling of layers during curing, additional distortions may occur after the part is removed from the platform due to the presence of internal forces developed during the fabrication process between the platform and the part. In case of PSL, just like all other radiation and layer based AM process, due to the layers of finite size discretization is also a well noticed problem. Also, parts made by SL have limited functionality because of their environmental stability, poor creep performance, low strength and stiffness. However, the part functionality can be increased by coating them with nickel copper or with their corresponding alloys.[4]

4 Microstereolithography

4.1 Introduction

Microstereolithography (µSL) works on the same manufacturing principle of stereolithography i.e. it builds 3D objects by stacking the layers where, each layer is fabricated by light induced space resolved photopolymerization of liquid resin. The resolution of µSL is much better than other rapid prototyping techniques as, SL has a typical resolution of 150 µm in the three direction of space where, µSL can even build the objects having details of few micrometer. Due to the better resolution and rapid manufacturing speed of µSL, it creates a great interest in both rapid prototyping and microengineering field.[6]

Due to the variations in the design of built apparatuses, µSL was known by many different designations i.e. IH process, spatial forming, 3D optical modeling, microphotoforming, microstereophotolithography, optical forming etc. But nowadays, it is known by the name "Microstereolithography", as it clearly demonstrates the connection of manufacturing process to both stereolithography and microfabrication field.[6]

µSL technology was firstly presented and developed by Ikuta *et al.* in 1992. It was named IH process (Integrated Harden Polymer Stereolithography). This system uses the UV lamp to fabricate the micro objects and had a resolution of 5 µm in the three direction of space. This system was successfully used to fabricate micro fluid parts and sensing calculation circuits such as, micro pipes, syringe, sensors, actuators etc. In 1996, Ikuta *et al.* also developed the Mass-IH process for the mass production of microstructures using optical fiber.[18]

Ever since the first development of µSL technique, researchers are formulating the strategies to improve the both lateral and vertical resolution of SL process, which classified the µSL fabrication processes in three different categories, named as,[6]

1. Scanning microstereolithography process
2. Integral microstereolithography process
3. Sub-micron microstereolithography process

Scanning microstereolithography processes is also known by vector-by-vector microstereolithography process. In this approach, a focused beam or lamp scans a fine spot on the resin surface according to the sliced two dimensional (2D) section. The formation of fine spot plays a key role in scanning µSL process and it is controlled by galvano-mirror or by translational X-Y stage. The integral microstereolithography process is also known as projection based microstereolithography process, in integral µSL process, patterned light generated by mask is projected and focused on resin surface according to the binary image generated from the sliced 2D section. Just like SL process, the main difference between these two methods lies in the curing method of each layer but rest of the fabrication approach is pretty much similar.[6,18]

Sub-micron microstereolithography is described in detail later in this chapter but in these processes the polymerization of layers composing the objects occurs directly inside the reactive medium rather than on its surface.[6]

4.2 Projection microstereolithography

As mentioned before, in Projection microstereolithography (PµSL), an image created or reflected by dynamic mask is projected on the surface of photosensitive resin in order to cure the 2D sliced section. Usually, liquid crystal display (LCD) or digital micromirror device (DMD) are used as a dynamic mask. The part to be manufactured is described by a series of black and white bitmap image files and then a dynamic mask is used to shape the light beam by using the bitmap files. Later that shaped light beam is focused on the resin surface by an appropriate optical system. The projected images solidifies the irradiated area and the duration of irradiation steps is controlled by using a shutter. Hence, a complex 3D object is fabricated in a same way as other conventional rapid prototyping techniques i.e., by superimposing many layers of different shape. A general schematic diagram of an projection microstereolithography apparatus (PµSLA) is shown in figure 4.1.[6]

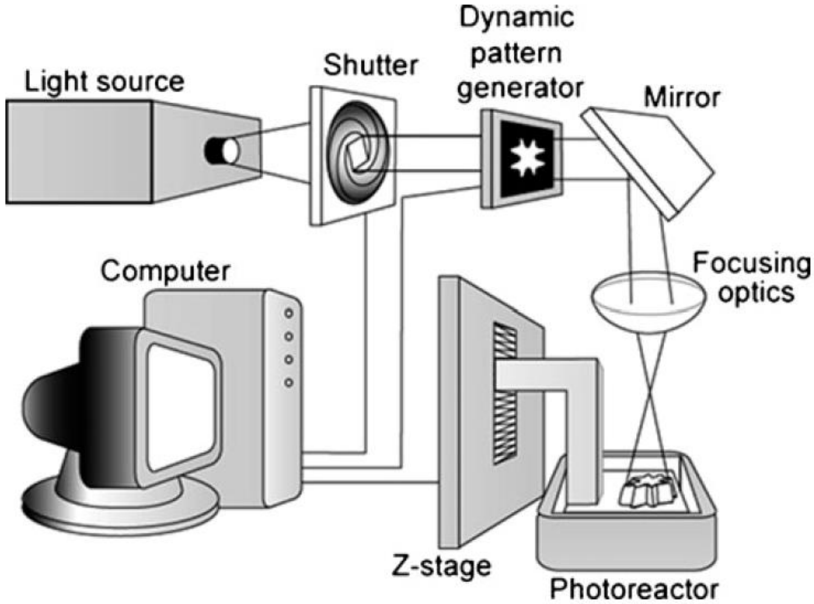


Figure 4.1 A schematic diagram of a PµSLA.[6]

PµSL is quiet faster than scanning microstereolithography, as the complete layer is irradiated just one single step despite of its complexity. Moreover the unwanted thermal polymerization can be avoided, as the light flux density on the surface of photopolymerizable resin much smaller in case of projecting an image rather than focusing a light beam in one point.[6]

4.3 Existing projection microstereolithography systems

PµSL is comparatively a new production technology with respect to other microfabrication technologies and it is still under research and experimentation so, there are variety of approaching methods. PµSL systems mainly vary depending on the chosen dynamic mask. So, According to the choice of dynamic mask, three different PµSLA have been explained in next part.

4.3.1 LCD based PμSLA

LCD is basically a flat panel display, which uses the light modulating properties of liquid crystals. The pixels in LCD can be set to their opaque or transparent state by changing the orientation of molecules they contains. In 1996, Bertsch *et al*. developed the first PμSL machine by using a LCD as a dynamic mask generator. In this apparatus, in order to achieve the high resolution, they used the laser beam expander, which expanded the laser beam to illuminate the largest possible surface area of LCD. Basically, the idea was to pass the necessary light with the pixels in their transparent state and to block the unnecessary light with the pixels in their opaque. So, as the light passed through the LCD, it contained the desired pattern of the layer. Later, that beam passed through the beam reducer and focused to resin surface, which selectively polymerized the irradiated area corresponding to the transparent pixels of LCD.[6, 14, 19]

At the time, when this PμSLA was built, LCDs were not compatible with the UV light, so this system operated in the visible light range. Despite of some general advantages like, fast manufacturing speed and freedom from unwanted thermal polymerization, there were also some limitations, which were noticed while experimentation on LCD based PμSLA. The major downside was the low resolution and the poor contrast of LCD. Only a circle containing small number of pixels are usable in LCD, which prohibit the fabrication of high precision parts. Moreover, the pixels in their opaque state does not completely stops the light, about 20% of the light can pass through them. In order to overcome this problem, a chemical reactive medium with polymerization threshold was used but this affected the vertical resolution of the system so, controlling of polymer formation in vertical direction became more challenging. In spite of all of these limitations, complex objects, having the resolution better than 5 μm in the three direction of space, were obtained by this system.[14,19]

4.3.2 SLM based PμSLA

Instead of using LCD as a dynamic mask generator, M. Farsari built a PμSLA by using spatial light modulator (SLM) as a dynamic mask generator. The main components used in apparatus were: an UV laser light source having wavelength of 351.1 nm, an optical shutter, a SLM, multi-element lithographic lens system and a high resolution translation stage. SLM is a special LCD component, which is not damaged by wavelengths longer than 350 nm.[20]

In this experiment, the SLM as illuminated by using UV light source and 2D slices of a 3D model were created along the chosen axis, at uniform increments. Then each images was converted into bitmap format and loaded onto the SLM which acts as a dynamic lithographic mask. In order to achieve the uniform energy distribution and maximize the contrast ratio of SLM, the nominally Gaussian irradiance distribution was reshaped to a rectangular uniform irradiance. The multi-element lithographic lenses were used which reduces the image by 10 or 20 times and focused it to the plane of the resin surface. Similar to the PμSLA developed by Bertsch *et al*. using the LCD as dynamic mask, the system was based on top down SL approach and the exposure time was controlled by using a shutter.[20]

The major advantage of using SLM rather than LCD as the dynamic mask was the possibility to use a UV light source. So, this system made it possible to utilize the existing wide range of commercial UV curable resin, which were made for conventional SL.

This SLM based PμSLA was able to build components with the dimensions in the range of 50 μm - 50 mm, having feature size up to 5 μm with the resolution less than 1 μm. In figure 4.2 a four pyramid structure made by this system, consisting of 45 layers and each having a thickness of 50 μm, is presented.[20]

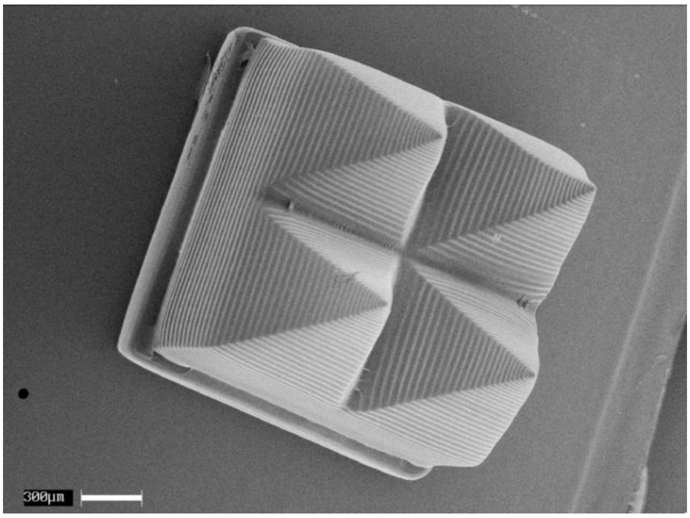


Figure 4.2 A four pyramid structure consisting of 50 μm thick layers.[20]

4.3.3 DMD based PμSLA

Digital micromirror device (DMD) consists of hundreds of thousands of small mirror and each mirror corresponds to a single pixel that can be turned on and off independently. More precisely, the micromirrors in the DMD can tilt at some specific angle by an electrostatic force and that tilted micromirror group makes the given pattern similar to binary image, which makes it possible to project the dynamically defined mask onto the resin surface by using a light projection device. Contrary to the approaches, in which LCD and SLM masks are used, in case of DMD, the light does not pass through the mask but is reflected from the chip.[18,21]

In case of DMD based PμSLA, the mask patterns are dynamically generated as bitmap images on a computer programmable array of digital micromirrors on the DMD chip. Then the light illuminated on the DMD chip is shaped according to the defined mask pattern and later the modulated light is passed through a reduction lens so that a reduced feature size image is formed on the curable resin.[21]

The DMD has many unique advantages over the conventional LCD and SLM chips. The DMD has smaller pixel size having narrow gaps between them, which allows higher display resolution and better uniform intensity. DMD allows faster switching speed which enables to control the exposure time more precisely. Furthermore, high modulation efficiency of UV illumination can be achieved by ultra-flat aluminum micromirrors, so process resolution can be enhanced by using UV light as shorter wavelength. Moreover, shorter wavelength corresponds to higher photon energy which implements the mechanical strength of polymerized microstructure.[21]

A brief comparison of LCD and DMD as a dynamic pattern generator is represented in the table 4.1.

Table 4.1 A comparison of LCD and DMD as a dynamic pattern generator.[21]

	LCD as Dynamic mask	***DMD as Dynamic mask***
UV compatibility	No	Yes
Modulation efficiency	12.5% (transmission)	88% (reflection)
Pitch size	(26 x 24) μm	(14 - 17) μm
Pixel size	(33 x 33) μm	(13 - 16.2) μm
Filling ratio	57%	91%
Contrast	100:1	350:1
Switching speed	20 ms	20 μs

Considering all of the above mentioned advantages of DMD, a DMD based PμSLA has been built in this thesis work.

4.4 Resolution in Projection microstereolithography

As mentioned before, depending on the movement of z-axis, there are basically two different approaches in which PSL system can be oriented i.e., top down orientation approach and bottom up orientation approach. There is also a third horizontal side-wise approach, but it is less traditional and is not used a lot.

In the top down orientation approach, the curing surface is free and the layer thickness is determined by the gravity, surface tension and the viscosity of fresh resin deposited on the free surface of the structure. Moreover, the layer thickness is also affected if number of layers increases and have complex and different geometry. In order to get rid of non-uniform layer thickness, the fresh resin deposited on the free surface should be smooth, so low viscosity resin can be used to manufacture the part since they do not require any smoothening or a sweeping blade can used which smoothens the surface of the resin before curing. But, sweeping blade will increase the manufacturing time and will eventually increase the cost of the system. Besides rough resin surface, oxygen inhibition is also a problem in top down orientation approach. Due to the presence of air, the outermost layer of cured object will not be completely cured due to the oxygen. So, the free surface would be cured better in the vacuum. Oxygen inhibition and smoothing of fresh resin layer can be achieved by putting a glass slide onto the resin surface, so that the curing occurs through transparent glass window. But the use of glass slide give rise to another problem that is, cured layer may stick to the glass slide.[22]

By considering all of the above mentioned facts, Bottom up orientation approach is used in the building of PμSLA. Since, in this case, the layer thickness does not depends on gravity, surface tension or the viscosity of the fresh resin but it can be precisely controlled by the gap between the glass and the platform. But there is one problem, which must be solved in order to successfully manufacture the parts. That is, the cured resin may stick to the glass slide instead of the building platform which leads to manufacturing failure. So, in order to avoid this problem, glass slide must be properly coated with special non-sticky coating, so that the sticking force between the cured part and glass slide is less than sticking force between the cured part and the platform. This adhesion phenomenon is explained briefly later in chapter 6.

4.4.1 Lateral resolution

Lateral resolution of PSL apparatus mainly depends on the used optics and the size of micromirrors in the digital micromirror device. Smaller the spot size of the focused light beam on the working platform will be, higher will be the resolution. So, a microscopic objective, which can produce the features of 1 µm size, can be used in order to focus the light beam. Focus should be exact the platform, as, the blurry focus decrease the resolution. Use of numerical aperture can increase the resolution but on the other side, the depth of the focus will be decreased. So, one should make sure that the depth of focus is larger than the layer thickness, otherwise, instead of constant lateral exposure, the cured layer will be hourglass shape like.[14,22]

The resolution is also affected by the properties of used resin, if the chain reactions in the resins are powerful. In this case, due to chain reactions and scattering of light, the polymer may get cured even outside of the exposed area. This phenomenon is not strongly noticed in case of few layers but in case of increased number of layers it strongly affects the overall resolution of the part. This phenomenon is mainly occurs in case of viscous resin or if the uncured resin does not change between layers. Overcuring of the resin also affects the resolution of the manufactured so, right exposure time should be used.[14,22]

4.4.2 Vertical resolution

The vertical resolution is not determined by the thickness of the liquid resin spread on the surface of the object being built but it depends on the polymerized thickness of the created layers and can be observed by free over-hanging parts. In order to improve the vertical resolution, the penetration of the light in the resin and the polymerization depth of the resin should be controlled consequently.[6]

Thin polymerized layers can be achieved by decreasing the exposure time of the chemical medium so that the energy received by the resin is close to the critical energy required to start the polymerization process. But, reducing the exposure time is not enough in order to achieve the low curing depth because the light may penetrate far into the resin even in the short interval of time. In order to achieve the micrometric resolution in vertical direction, one can also alter the properties of resin by utilizing the neutral absorber. Neutral absorber are nonreactive chemicals that absorbs the light and dissipates the captured energy without interfering the photopolymerization process. The addition of neutral absorber in the resin is quiet efficient way to reduce the polymerized thickness of the resin, but they reduce the reactivity of the resin i.e., the required energy to initiate the curing process will be increased. So, exposure time needs to be increased in order to start the polymerization process, which leads to low manufacturing speed.[6]

4.5 Two-photon polymerization

Two-photon polymerization technique is also a microfabrication technique, which differs from conventional scanning and integral microstereolithography processes as in this case, the part is manufactured directly inside the reactive medium rather than on its surface. The 3D microfabrication with two photon absorbed photopolymerization was initially proposed by Maruo *et al*. in 1996.[6,23]

Two-photon absorption is a nonlinear phenomenon which occurs in all materials, when the combined energy of two photons matches the transition energy between the ground state and an excited state, in the presence of high irradiance. The two-photon absorption rate is proportional to the square of the incident light intensity. The quadratic dependence on the light intensity confines this phenomenon to the area at the focal point, which confines the photopolymerization phenomenon in submicron volumes.[6]

Very tiny objects, having submicron resolution, have been built by using two-photon polymerization process and this polymerization process may even reach the resolution of sub-50 nm.[24] A sculpture of micro-bull manufactured by using two photon polymerization process is presented in the figure 4.3. The sculpture is about the size of a red blood cell, having dimensions 10 μm long and 7 μm high.[25]

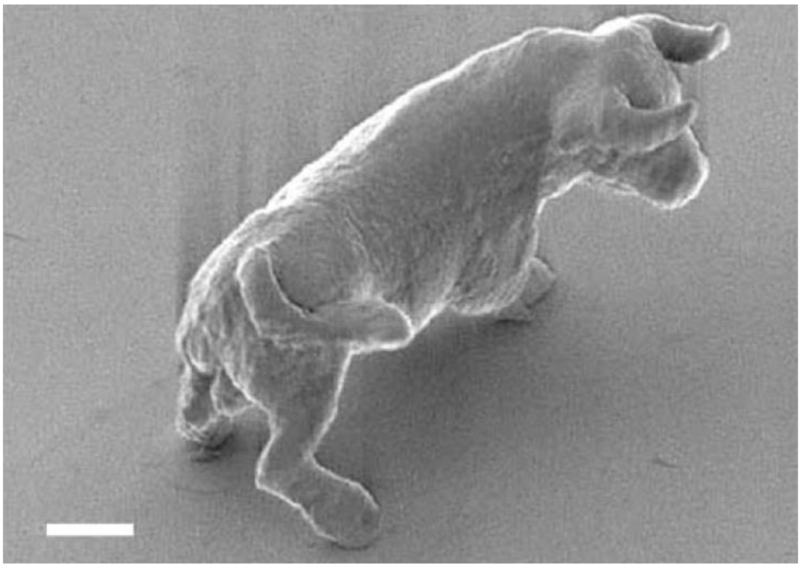


Figure 4.3 A sculpture of micro-bull manufactured by using two-photon polymerization.[25]

4.6 Business potential of microstereolithography

Microstereolithography is a under research microfabrication technology which is not commercially available up till now. Even though, some service bureaus are utilizing this technology to manufacture complex miniaturized objects which are way too hard or impossible to produce by other conventional rapid prototyping techniques. The first development of μSL machines started in 1993 and from then, different research team have developed their own machines, implementing specific features by using specially developed resins.[6]

Due to the much better resolution of μSL than other RP techniques, this technology creates a particular interest in the micro-engineering domain where its 3D compatibility allows to manufacture the components which no other microfabrication technology can create. The compatibility of μSL with other conventional microfabrication has been estimated in specific cases and the only limitation of μSL in Microsystems field is that, it is not a wafer-level collective fabrication technology yet.[6]

μSL has been successfully used to produce the components for micro-robotic, micro-fluidic, Microsystems and biomedical applications. Currently, the developments have been made to extend the choice of materials that can be used in this process and many biocompatible and biodegradable resins have been developed so far. Components in composites materials have also been produced by μSL machines, which allows it to manufacture 3D microcomponents in ceramics or metals.[6] Besides this, μSL has also been successfully used to produce multi-material microstructures. So, it can also be used to produce multi-material microscaffolds for tissue engineering.[26]

5 Building of a Microstereolithography device

The main objective of this thesis was to build a LED based Projection Stereolithography apparatus, which can manufacture 3D objects with microscopic accuracy and details. The main requirement of the thesis was that the constructed setup should be able to attain the micrometer details in both lateral and vertical direction. But, due to some technical difficulties and limited time, the fabrication of fine detail 3D microstructures is postponed.

5.1 Required apparatus

Due to the various advantages of bottom up orientation over the top down orientation, as mentioned in the previous chapters, a bottom up oriented PµSLA has been build. The apparatus is built by following the principle that the solid microstructures should be able to produce by focused light, which is projected over the surface of photo-curable resin and undergoes a photopolymerization process to fabricate the desired solid microstructures. So, in order to build a working microstereolithography device following equipment are required.

i. A light source, which will be focused on the photo-curable resin.
ii. A digital micromirror device (DMD), to generate the desired patterns.
iii. Optical components, to focus the light source on the photo-curable resin.
iv. A transparent resin vat, in which liquid resin will be placed.
v. Platform, with which the constructed micro-part will be attached.
vi. A computer controlled elevation device, to control the vertical movement of the stage.

A brief schematic of suggested DMD based microstereolithography apparatus has been shown in figure 5.1.

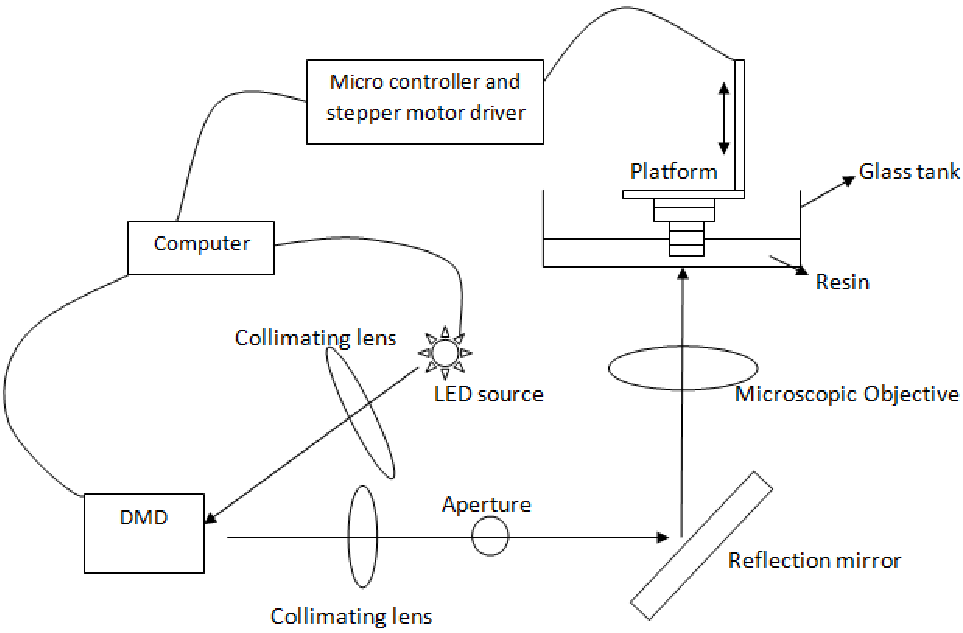


Figure 5.1 Schematic of the suggested DMD based PµSLA.

5.1.1 Light source

In microstereolithography apparatus, a laser or lamp can be used as a light source. In this research work, a true violet UV LED having a wavelength of 410 nm has been used.[27] A general picture of LED used in the setup is shown in the figure 5.2.

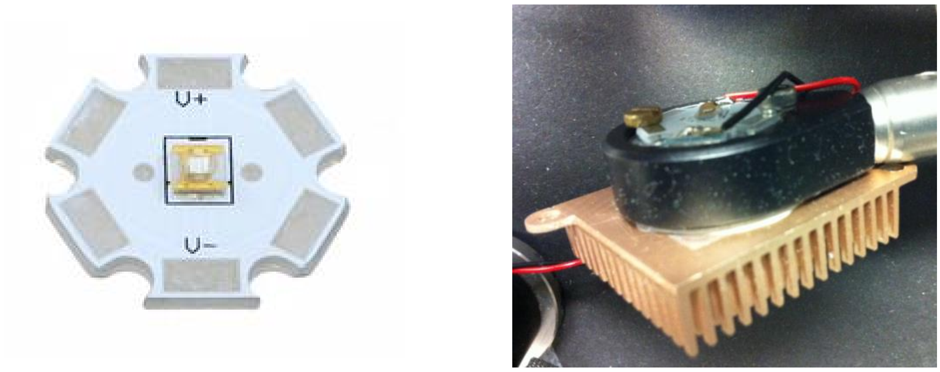


Figure 5.2 UV LED used in the setup.

Normally, in PμSLA, a commercial video projector is usually used. Video projector is basically consists of both the light source and the DMD with various optical components, which guide the light inside the projector from the lamp to the DMD. But the downfall of using the video projector is that the intensity of the video projector lamp light is not uniform, which give rise to the hotspot compensation. In order to avoid the hotspot compensation, one has to use the intensity corrected background image. The intensity corrected background image is a grayscale image that uniforms the intensity difference between different areas. Whereas, on the other hand the LED has uniform light intensity. So, in order to avoid the hotspot compensation, an UV LED is used as a light source in the construction of PμSLA. Secondly, the used LED source has operable wavelength i.e. 410 nm, which has enough energy to keep the exposure time within seconds, which also eliminates the need of use of bandpass filter. Figures 5.3 and 5.4 shows the uniform intensity distribution of LED.

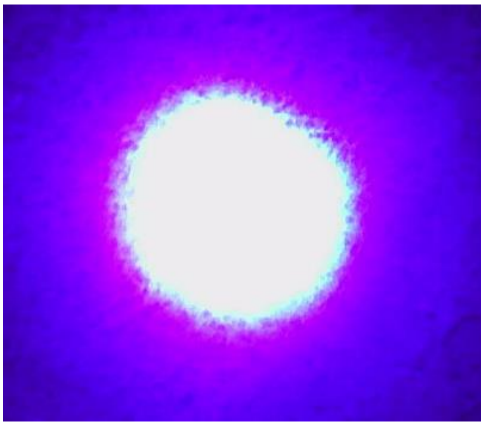


Figure 5.3 The output image of the projected light at the bottom surface of the resin vat.

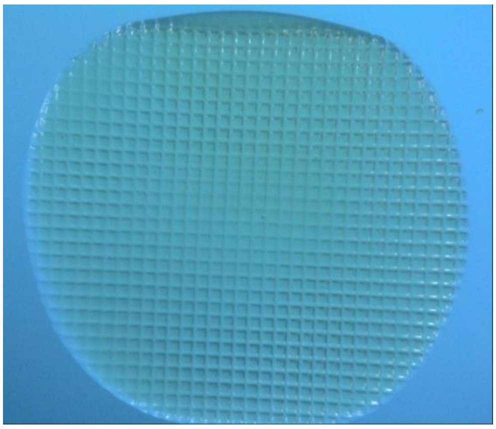


Figure 5.4 A cured single layers of small squares representing the uniform light intensity.

5.1.2 Digital micromirror device

In PμSLA, the digital micromirror device plays a great role in the making of dynamic patterns. It is faster than scanning based microstereolithography, since it does not need time to scan the layers. The DMD and the motherboard used in the built setup is obtained from OPTOMA HD20 digital light processing (DLP) projector. DMD is consists of tiny micromirrors and each mirror corresponds to the single pixel. The native resolution of the projector is 1920x1080, which means DMD consists of 2073600 tightly packed micromirrors. The micromirrors in the DMD can tilt at a specific angle (±12°)[18] by an electrostatic force. The tilted micromirror generates the given pattern, which is similar to binary image i.e. black and white, resulting in the reflection of patterned light to the microscopic objective, which later projects the light to the resin vat. Figure 5.5 shows the DMD used in the built setup, whereas, a magnified micromirror array, tilted at some specific angle, is shown in figure 5.6.

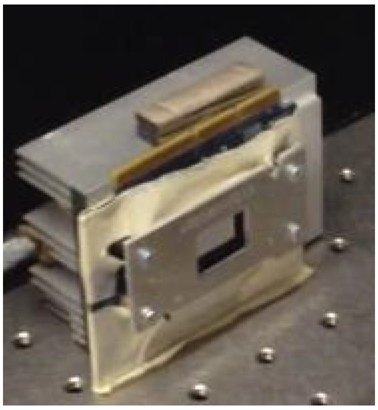


Figure 5.5 DMD used in the setup.

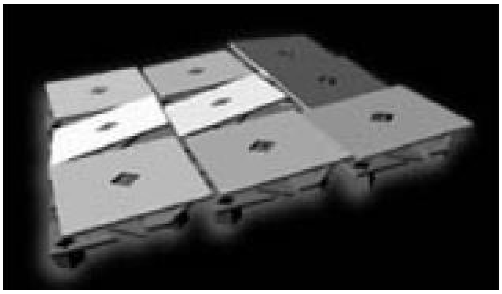


Figure 5.6 Magnified micromirror array.[18]

The micromirrors in the DMD, either stays in their flat state or tilt ±12° (along its diagonal line) depending on the generated black and white image. White image tilt the micromirrors to +12° which reflects the positive image light and black image tilt the micromirrors to -12° resulting in the reflection of negative image light (also called dummy light). While, the flat state of micromirrors is non-energized state. So, if the incident angle of the light is 24° against the flat mirror surface, +12° tilted micromirrors reflects the light in the normal direction of the flat state mirror, whereas, flat and -12° tilted micromirrors reflects the light away from the normal direction of the flat state mirror. Figure 5.7 shows the reflected light path according to the tilt angle of the micromirror.

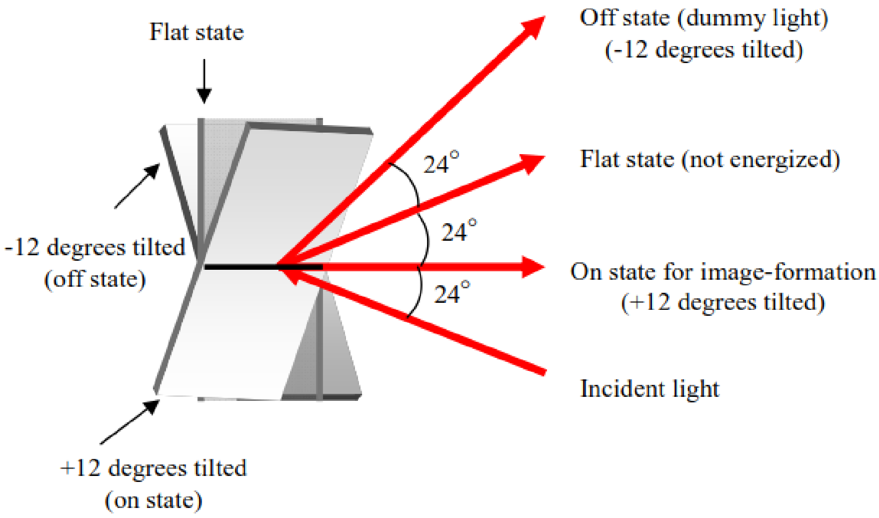


Figure 5.7 Reflected light path according to the tilt angle of the micromirror.[18]

So, while adjusting the setup, the optical axis of the projection lens should be same as the normal direction of the DMD surface, so that only the patterned light, reflected by +12° tilted micromirrors, is focused on the resin surface.

5.1.3 Optical components and their adjustment

Optical components and their adjustment plays a key role in the projection based microstereolithography process, since the lateral resolution of the fabricated object depends primarily on the used optics. In order to achieve micrometer resolution along lateral direction, the area of one pixel projected at the bottom surface of the resin vat should be around a couple of square micrometers. In the built PμSLA, in order to achieve a good lateral resolution, two collimating lenses, an aperture, a reflection mirror and a microscopic objective have been used.

When the lens system is used to focus an object, there are always some errors between an object and the focused image and it is impossible to perfectly remove those errors. The typical errors in the optical system are aberrations and diffractions. The main well known aberrations are spherical and chromatic aberrations. Spherical aberrations are due to the manufacturing defect and imperfection of lens shape while, chromatic aberrations occurs due to the different refractive index according to the wavelength. Diffraction affects the resolution according to the wavelength of the light and the numerical aperture of the lens.[18]

In the built setup, firstly the incident angle of light from LED source is adjusted against the flat mirror surface of the DMD at an angle of 24°, so that the +12° tilted micromirrors reflects the light in the normal direction of the surface of DMD and a collimating lens is used in order to deliver the light with uniform intensity and of proper size to the DMD surface. Light reflected by the DMD also diffracts a little bit and in order to collimate that another collimating lens with a focal length of 11 cm has been used. The collimating lens generated a diffraction pattern as shown in the figure 5.8, so a variable aperture has been used in order to compensate the diffraction pattern.

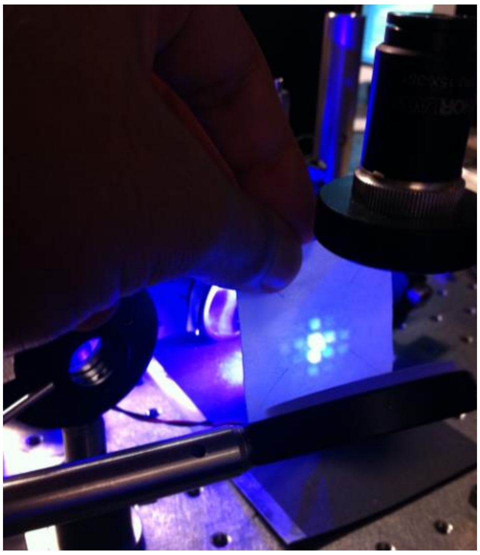


Figure 5.8 Diffraction pattern created by collimating lens on the surface of reflection mirror.

Finally, a microscopic objective, in order to create a fine projection with microscopic dimensions on the bottom surface of resin vat and a reflection mirror, which reflects the light coming from DMD to the microscopic objective, are used. In order to control the focus point, both the reflection mirror and microscopic objective are controlled by micrometer adjuster and to stop the unwanted reflection of the light, the shiny surfaces of the used apparatus are coated with black paper.

A brief configuration of the optical components is demonstrated in the figure 5.9. Whereas, the top view of the adjusted apparatus is shown in the figure 5.10.

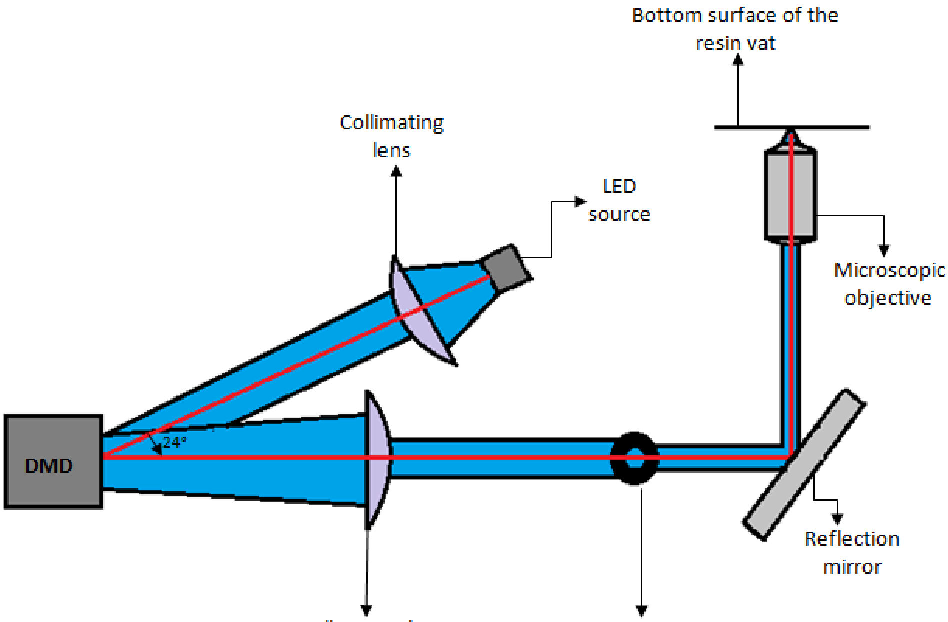


Figure 5.9 Configuration of optical components according to the principal ray.

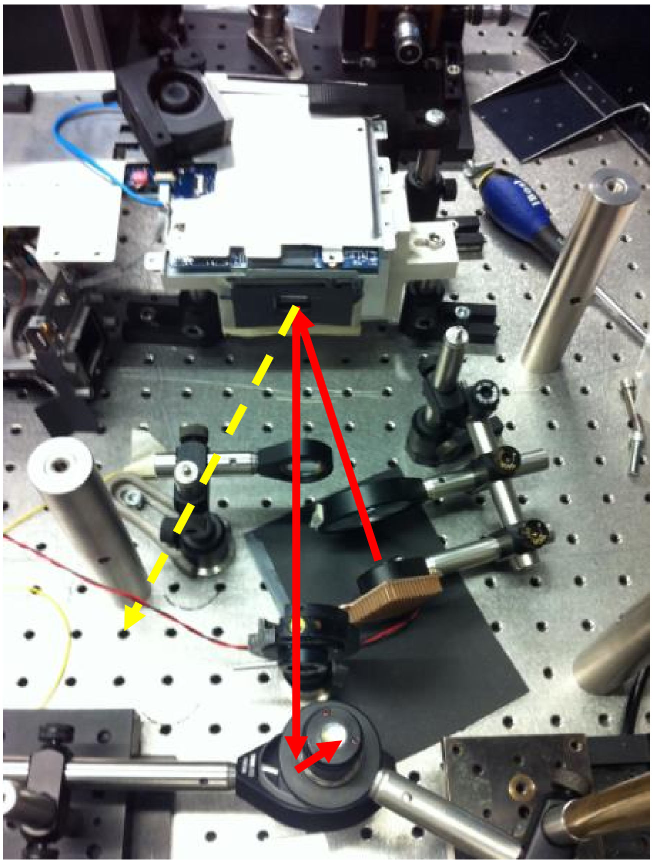


Figure 5.10 Top view of the adjusted optical components. (Red line shows the principal axis of the light rays, where yellow dashed line show the negative image light.)

5.1.4 Reisn vat

Resin vat should be non-sticky in nature, so that the force between the platform and the cured layer is greater than the force between the resin vat and the cured part. Otherwise, the cured part will stick to the resin vat leading to the manufacturing failure. Beside this, the resin vat should be transparent, so that the image can form on the inner bottom surface of the resin vat without any blurriness, otherwise the resolution of the system will be affected.

5.1.5 Platform

Platform should be as smooth and small as possible, as, the layer thickness is difficult to control in case of larger platform area. Hence, a platform having an area of approx. 0.6 mm^2 has been used, shown in the figure 5.11.

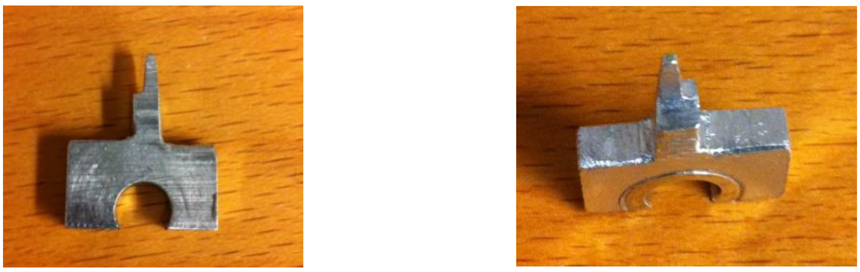


Figure 5.11 Platform used in the apparatus.

5.1.6 Elevation device

The vertical elevation of the PμSLA is controlled by using a geared stepper motor. Stepper motor is a brushless DC motor, which rotates in a stepping manner when a voltage is applied on the motor terminal. If the motor is carefully sized to the application in respect to speed and torque, the motor can hold or move the position of the shaft without any feedback sensor. The stepper motor can be used as a linear actuator in order to achieve an accurate linear motion. Circular motion of the stepper motor can be converted into a linear motion by using screws and gears. A geared stepper motor used in the PμSLA is the same as the one used by Lehtinen Pekka[14] in his PμSLA, shown in the figure 5.12.

Figure 5.12 A geared stepper motor used in built PμSLA.

As shown in figure 5.13, in order to achieve the linear movement, a M6 threaded rod is coupled to a threaded motor shaft. The translational stage is attached to the threaded rod and in order to avoid any rotational or vertical movement the stepper motor has been fixed to the fixtures. As the shaft rotates the translational stage moves in the vertical direction. The coupling of the rod to the stepper motor should be as rigid as possible in order to avoid the backslash and the unwanted movement.

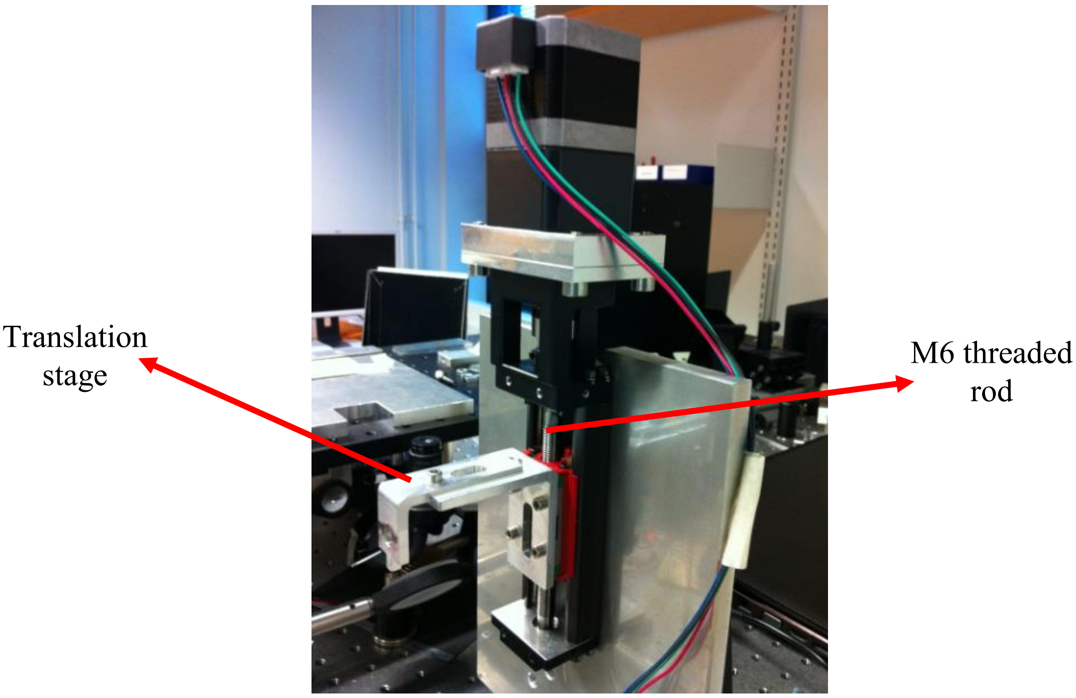


Figure 5.13 A stepper motor connected to a M6 threaded rod and a linear translational stage.

The linear movement accuracy is determined by the pitch of the screw rod attached to the stepper motor. The smaller the pitch the more the shaft has to rotate to attain the required distance. The used M6 thread has a pitch of 1 mm i.e. one full revolution will result in the vertical movement of 1 mm of the translational stage. In the built PμSLA, the geared stepper motor has a planetary gearbox, of gear ratio 13,73:1, attached with a 200-step stepper motor. So, in order to achieve one full revolution, 2746 (13,73 x 200) steps are required. Thus, the step distance for the M6 thread rod is 0,364 (1000/2746) μm/step. So, the step size accuracy meets the 1 μm step size requirement of PμSLA.[14,28]

The stepper motor is controlled by using an EasyDriver stepper motor driver and Arduino Uno microcontroller. The EasyDriver splits the stepper motor steps into microsteps, making the rotation smoother. The connections between computer, Arduino Uno micro controller and EasyDriver are shown in the figure 5.14. Showing 1) USB-B port for the computer connection, 2) STEP and DIR pins, for communication between the stepper motor driver and the microcontroller, 3) Connection to Stepper motor, 4) Power supply connection and 5) GND (Ground) pins.

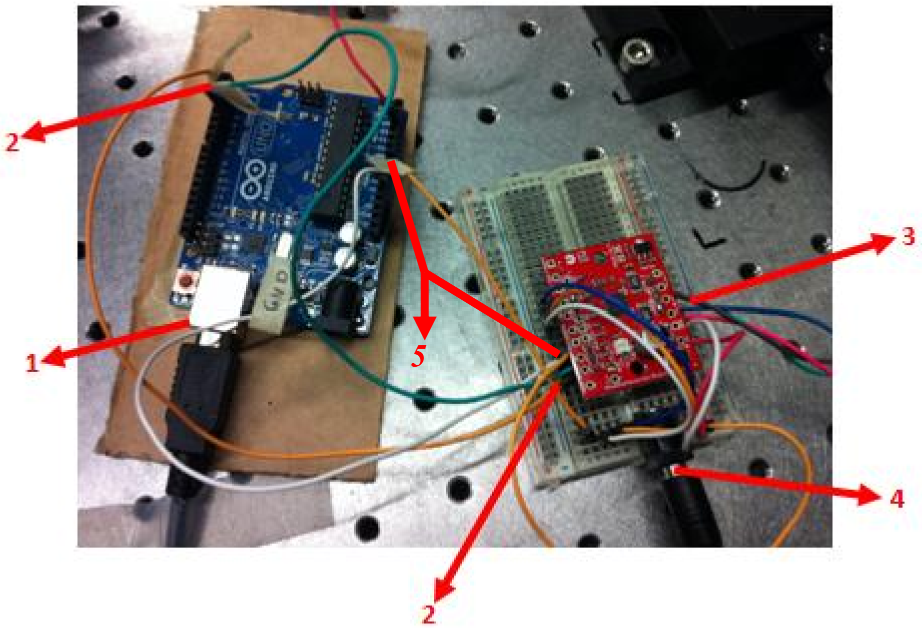


Figure 5.14 Connections between computer, Arduino Uno microcontroller and EasyDriver.

The whole PμSLA is shown in the figure 5.15. Showing, 1) LED source, 2) Digital micromirror, 3) Collimation lenses, 4) Aperture, 5) Reflection mirror, 6) Microscopic objective, 7) Resin vat, 8) Platform, 9) Elevator

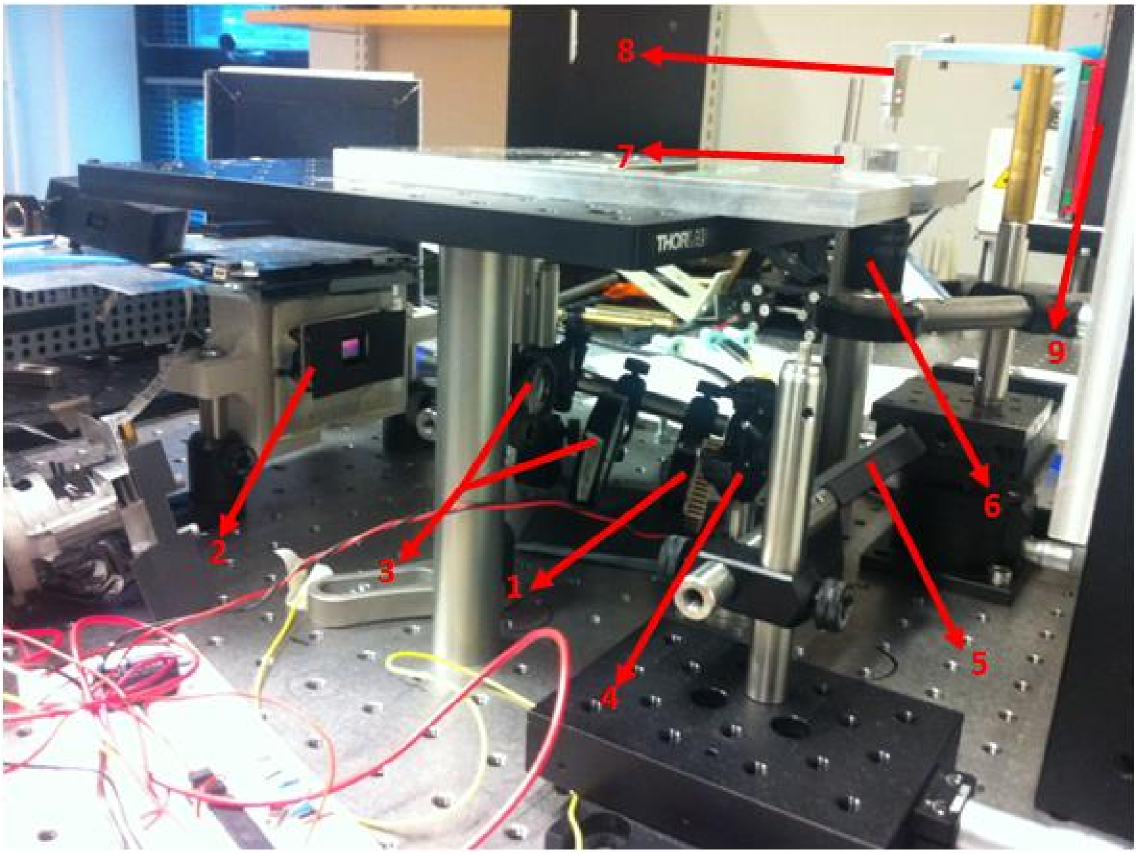


Figure 5.15 The built experimental setup for PμSL process.

5.2 Operation Program

The DMD is connected to the computer via HDMI cable and shares the same screen as of the monitor. The idea is to have a slide show program, synchronized with movement of the motor, to control the image projection. In order to start the manufacturing process, two different programs are required. One program is required to control the projection of image synchronized with the movements of the stepper motor and it should be able to adjust the operation parameters such as, exposure time, delay before and after the layer has been cured, layer thickness, motor movement speed etc. While one program is required for controlling the stepper motor. The microcontroller must accept the input values sent from the computer and move the stepper motor accordingly. The slideshow and the z-motor must be properly synchronized, if an image is projected while the motor is still moving, the fabricated structure will be destroyed. So, the computer program should project images only when the motor is at rest and there is a new layer of fresh resin between the resin vat and the platform

Both of the programs were written by Mr. Lehtinen Pekka and Mr. Verho Tuukka. The graphical user interface (GUI) of the computer program is presented in figure 5.16. As shown in the figure 5.16, the user can control the exposure times, post exposure and movement delay, layer thickness and liftoff distance of platform after the layer has been cured by simply inserting the numerical values in the desired cells. Whereas, the motor speed, acceleration, distance covered by one revolution and step angle is also user dependent and changeable. The platform can also be able to stopped or moved up and down with an interval of 10 μm by sliding the bar or move to any distance by inserting the integral value in the box present on the mid left.

The program is started by uploading the folder of images of cross-sections by pressing the browse button, present in the top mid of the GUI and then by pressing the "start printing" button present on the top right corner. Once the start printing button will be pressed, the screen will turn black and the manufacturing process will start by pressing the "s" key. After curing all of the layers, the screen will again turn black and program can be shut down by pressing the "ESC" key.

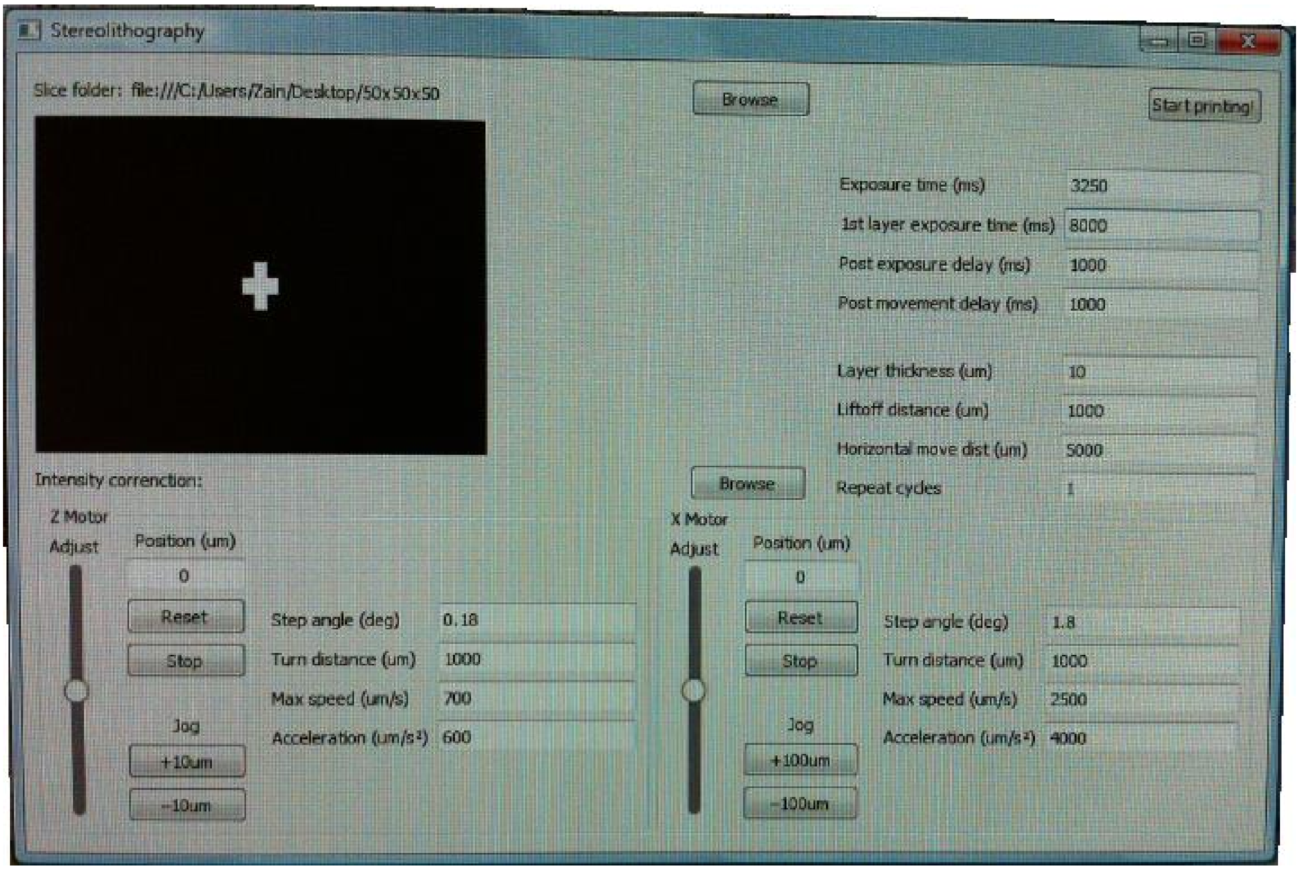


Figure 5.16 The graphical user interface (GUI) of computer program.

6 Experimentation and Results

6.1 Preparation and slicing of images

In order to manufacture a part, firstly the CAD model of the part should be converted into a STL file and then the STL should be sliced into black and white images. In this thesis work, the slicing of an STL file is done by "Creation workshop" software. Creation workshop is an easy to use SLA slicing and control software. It provides multiple options for controlling the slicing. One can easily modify the output file type, resolution, size, layer thickness and number of slices of the uploaded STL file.

A brief example of the use of the software is presented by slicing an STL file of a propeller like structure presented in figure 6.3. In order to create the slices of the desired model, firstly the STL file of the CAD model is uploaded in to the creation workshop software. One can easily change the orientation and size of the model by rotate and scale % tabs present on the right of the main screen. The model should be presented in right orientation i.e., the bottom surface of the model should be in xy-plane and the positive z-axis of the model should align with the positive z-axis of the platform presented in the software. Because, the slicing of the model is done in the presented orientation and later the part will be manufactured according to it. If the model will be oriented upside down or in sideways, it may be impossible to fabricate the structure if it has a complex geometry, unless supports are added for the fabrication.

Once the orientation of the model is adjusted, the machine configuration properties should be adjusted, as the final resolution of the output files depends on machine configuration properties. If the adjusted resolution of the output files is not same as the resolution the DMD, the lateral resolution of the PμSLA will be affected and the fabricated layers will be blurt. Finally, in order to slice a model into images, a slicing profile must be set up. Slicing profile allows the user to modify the slice thickness, the core and cavity parameters and the orientation mode for the slicing of the model.

After setting up the slicing profile, images can generated by simply selecting the slice icon  from the toolbar.

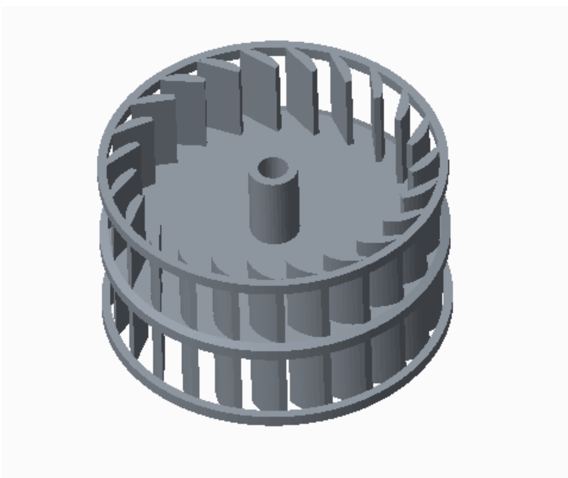
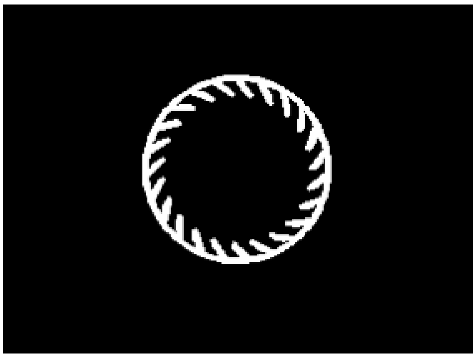
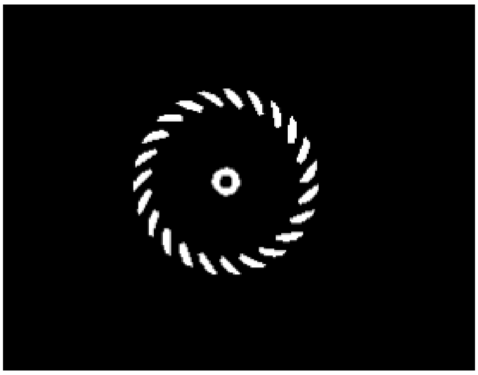


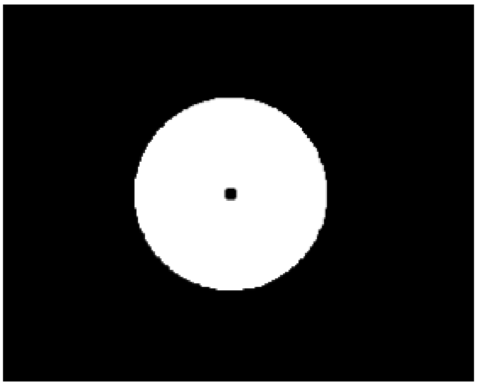
Figure 6.1 CAD model of a propeller like structure.



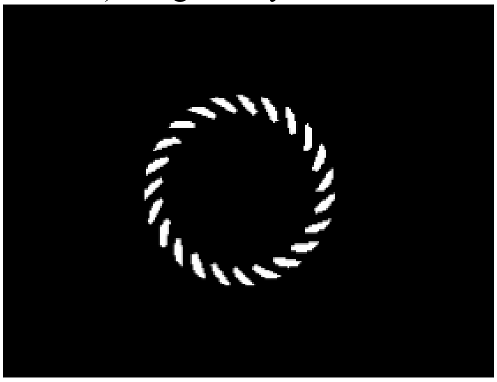
a) Image of layer 4/128



b) Image of layer 20/128



c) Image of layer 60/128



d) Image of layer 114/128

Figure 6.2 Sliced images of the CAD model of propeller like structure.

6.2 Minimum size and lateral accuracy

The goal of the thesis work was to built a PµSLA that can be used to fabricate micro-structures. In the built setup, the microscopic objective focuses the light on the area of roughly 3.6 mm^2. In order to calculate the size of one pixel, a layer of gird of squares has been cured, as shown in the figure 6.1. In the cured layer of the grid, the squares have dimension of 24x24 pixels, while the lines between them have a width of 8 pixels, which results in producing a layer of exposure length equals to 2133 µm consists of 832 (26*(8+24)) pixels. Hence, the width of one pixel is equals to 2.56 µm.

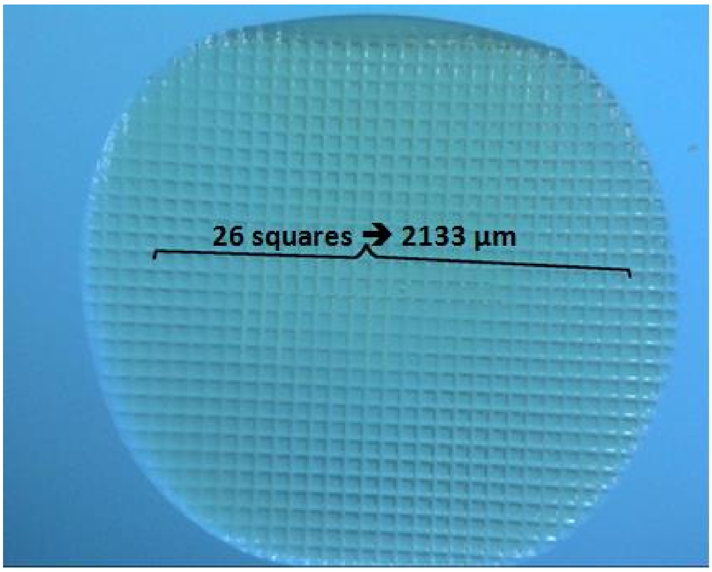


Figure 6.3 A layer of grid of squares showing the lateral resolution of the built PµSLA.

The built setup can also manufacture the objects having the dimensions of up to 1 pix-el, as shown in the figure 6.2.

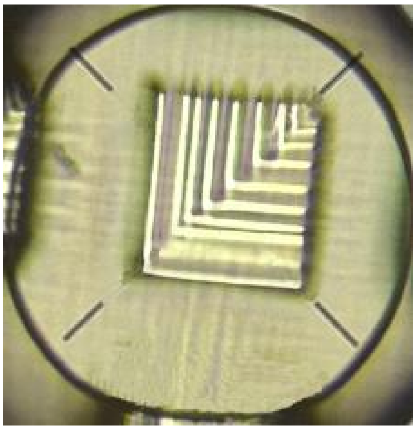


Figure 6.4 Cured layer consisting of lines having dimension of 1 pixel.

6.3 Resin

In the project, one laboratory-made and two commercial resins have been used and tested for the fabrication purposes. Laboratory-made resin consists of trimethylolpro-pane trimethacrylate as a monomer, Lucirin TPO-L as a photoinitiator and Disperse orange 13 (having dye content of 90%) as a neutral absorber. Where in the commercial resins, pic-100 and HTM140 V2 have been tested. Both the commercial resins are easi-ly available and long penetration depth resins. The curing times of the tested resins are shown in the table 6.1.

Table 6.1 Curing time of the experimented resins.

Resin	***Curing time***
Pic-100	450 milliseconds
HTM140 V2	150 milliseconds
Laboratory made	2800 milliseconds

Generally, the manufacturing process is bit difficult in the case of short penetration depth resins. As, the distance between the bottom surface of the resin vat and the plat-form must be less than the maximum curing depth of the resin, so in case of short pene-tration depth resin, the gap is extremely short and the platform must be positioned at a distance less than the maximum curing depth of the resin. Too large gap will destroy the entire fabrication process. The positioning of the platform near to the bottom sur-face of the vat is not very easy, since there are not any designed equipments for meas-uring the distance between platform and resin vat. Sometimes the bottom surface of the resin vat is also coated with some soft non-sticky material, so if the platform touches the vat surface, it may destroy the coating material.

6.4 Coating material for resin vat

In bottom up orientation approach SL, a resin layer is cured between a platform and the bottom surface of resin vat, hence the cured layer will strongly stick itself to both the vat and platform surface. As, the platform is moved up the fabricated part will be ripped off either from the platform surface or from the resin vat surface, depending on where the adhesion strength will be weak. But, if the adhesion strength is strong on both interface, the fabricated part may also torn apart. As mentioned before, in bottom up SL process, it is necessary that the fabricated part should be separated from the resin vat. Therefore, the adhesion strength between the cured part and the resin vat should be weak as possible and at least weaker than the adhesion strength between the cured part and the platform.[29]

In order to make this possible, either a non-sticky resin vat is used or the inner bottom surface of the resin vat should be coated with some non-sticky material. In order to be adequate for the purposes of SL, the coating material must fulfill below mentioned three specific factors.[29]

1. Firstly, the sticking force between the cured part and the platform should be stronger than the sticking force between the cure part and the resin vat.
2. Secondly, the coating material must possess good optical properties i.e., the light should be able to pass through it without being distorted. But the small distortions might be acceptable, if the wanted resolution is achieved.
3. Lastly, the material should have good mechanical properties because if the cured part tears away a small piece of coating material after the fabrication of each layer, the final manufactured part will be damaged or may stuck to the resin vat when no coating material will be left.

Besides using the non-sticky coating material, the peeling method can also be used in order to reduce the pull up force. In this case, the substrate is tilted slightly before the pulling it up so that the force will exerted only to the edge of the cured part. As a result, the part will is peeled off from the vat surface instead of being pulled up and the required force to detach the built part will reduce significantly.

In the built PμSLA, following three coating materials have been tested.

- DIARC® Cromo
- Teflon AF-2400X
- PDMS (Polydimethylsiloxane)

DIARC® Cromo coating is basically developed for molding applications. It exhibits great hardness with excellent release property, but it does not perform well in case of SL technology, the results are shown later in this chapter. Teflon AF 2400 is an amorphous fluoropolymer transparent film with an excellent oxygen permeability and chemical inertness. Since, oxygen inhibition give rise to incomplete cure when photopolymerization is conducted in air, Teflon AF 2400 being oxygen permeable film creates a thin uncured liquid layer between the film and the cured part surface, also known as "dead zone". A dead zone created above the film maintains a liquid interface below the cured part, hence the cured part only sticks with the platform. Teflon AF 2400 films have been previously used by Joseph M. DeSimone in continuous liquid interface production (CLIP) of 3D objects with the feature resolution below 100 micrometers.[30]

A brief illustration of bottom up SL process in the presence of oxygen permeable window is shown in the figure 6.5. In this project, in order to create an oxygen permeable window, a Teflon AF 2400X film having a nominal thickness of 80 μm has been tested.

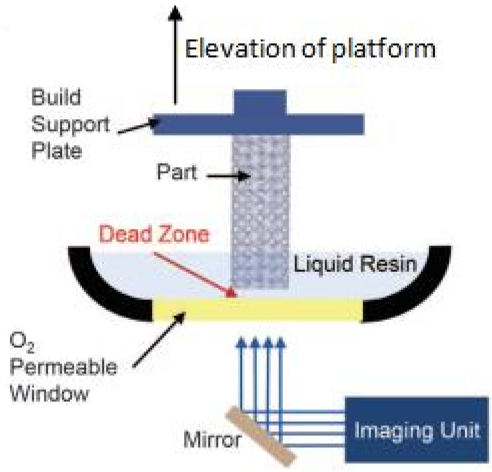


Figure 6.5 Bottom up PSL technique in the presence of oxygen permeable window.[30]

Polydimethylsiloxane (PDMS) is an optically clear, inert, non-toxic and non-flammable silicone based organic polymer. It is also quiet common in the field of SL. In this project, a petri dish with a thick layer (>2 mm) of PDMS has been tested.

An oxygen permeable window created by Teflon AF2400X film and a petri dish with the coating of PDMS is shown in the figure 6.6.

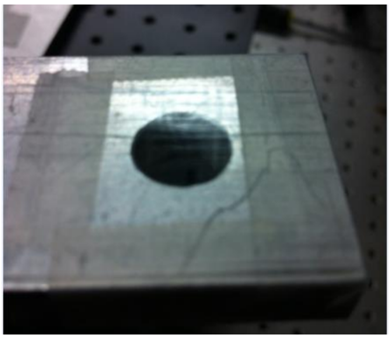


Figure 6.6 O_2 permeable window created by Teflon AF2400X film and a petri dish with a thick coating of PDMS.

In order to check the fabrication accuracy of the built PμSLA, a structure consists of a base layer and three different sized squares have been fabricated by utilizing the above mentioned coatings and resins. The results of fabrication are presented in figures later in this chapter, in correspondence to applied coating and used resin.

6.4.1 DIARC® Cromo

Firstly, a microscopic slide having a coating of DIARC® Cromo has been tested as a resin vat. But, it is not suitable for the manufacturing purpose as, it results in a complete manufacturing failure. The failed part is shown in the figure 6.7. As, one can see that the cured resin does not detach from the coated slide and does not stick with the platform, showing that the adhesion strength between the cured resin and the coated slide is greater than the adhesion strength between the cured resin and the platform. So, the fabrication process does not even begin.

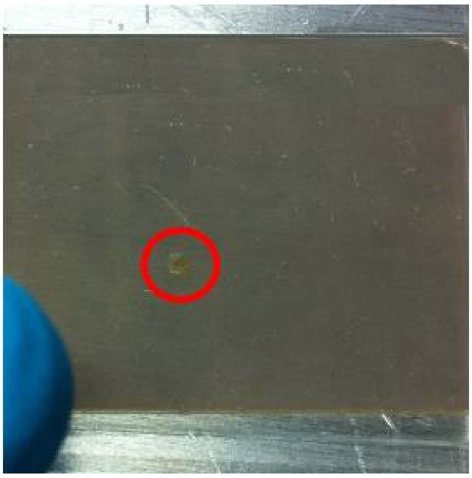
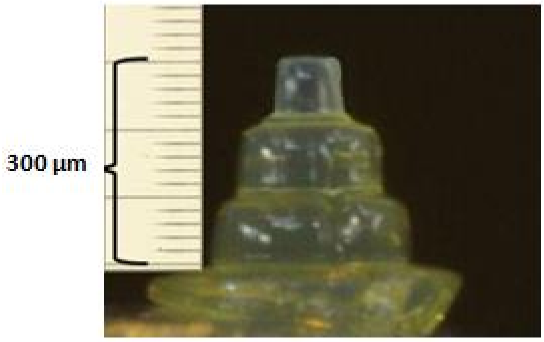


Figure 6.7 Cured resin (shown in red circle) stuck with a microscopic slide having a coating of DIARC® Cromo, resulting in manufacturing failure.

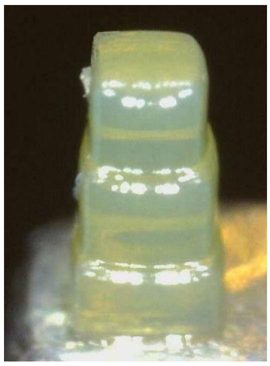
6.4.2 Teflon AF2400X

An oxygen permeable window has been created by using the Teflon AF2400X films with the nominal thickness of 80 µm as shown before in figure 6.6. In order to test curing process through oxygen permeable window, three different sized squares consisting of 30 layers (10 layers of each square) have been fabricated by using HTM140-V2, pic-100 and laboratory made resins.

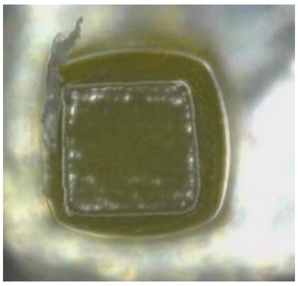
For HTM140-V2 resin, the exposure time for base layer was 1.2 second while for successive layers 150 milliseconds was selected. The fabricated parts are shown in the figure 6.8. The images are taken by digital microscope. As, the digital microscope is a bit difficult to handle, that's why the images a little bit blurt.



(a) Fabricated structure consisting 10 µm thick layers followed by a base layer and squares of sizes 200x200, 150x150 and 100x100 pixels.



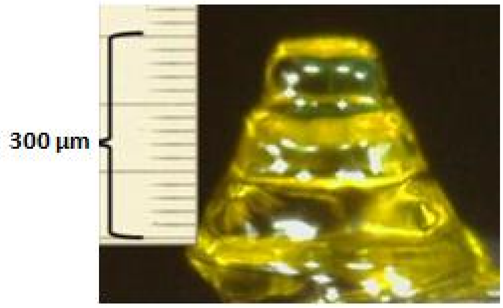
(b) Fabricated structure consisting 30 µm thick layers followed by a base layer and squares of sizes 300x300, 250x250 and 200x200 pixels.



(c) Top-view of fabricated structure consisting 30 µm thick layers followed by a base layer and squares of sizes 300x300, 250x250 and 200x200 pixels.

Figure 6.8 Structures fabricated by HTM140-V2 resin through oxygen permeable window created by Teflon AF2400X.

Secondly, same structures were constructed by curing Pic-100 resin. In this case, the curing time for base layer was 2 seconds while for the other layers 450 milliseconds was selected. The fabricated structures are shown in the figure 6.9.



(a) Side-view of fabricated structure consisting 10 µm thick layers followed by a base layer and squares of sizes 200x200, 150x150 and 100x100 pixels.

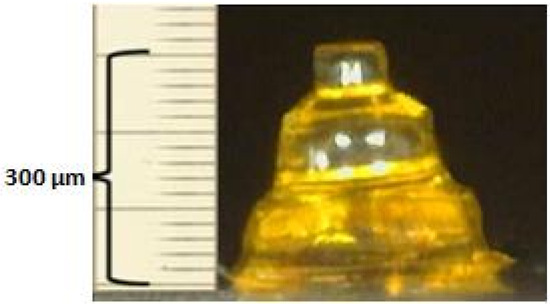
(b) Top view of fabricated structure consisting 10 µm thick layers followed by a base layer and squares of sizes 200x200, 150x150 and 100x100 pixels.

(c) Side-view of fabricated structure consisting 30 µm thick layers followed by a base layer and squares of sizes 300x300, 250x250 and 200x200 pixels.

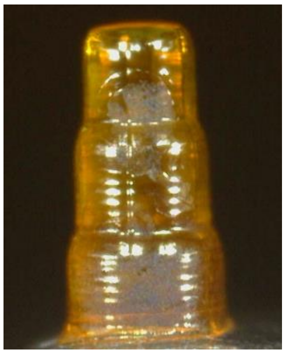
(d) Top-view of fabricated structure consisting 30 µm thick layers followed by a base layer and squares of sizes 300x300, 250x250 and 200x200 pixels.

Figure 6.9 Structures fabricated by Pic-100 resin through oxygen permeable window created by Teflon AF2400X.

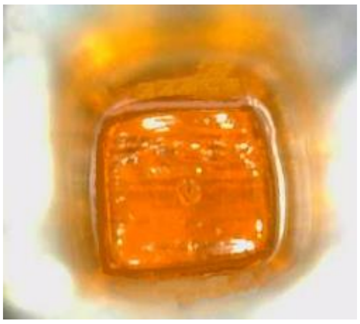
Finally, the fabrication accuracy was tested by using the laboratory made resin by constructing the same structures. Laboratory made resin contains Disperse orange-13 as a neutral absorber. Hence, neutral absorber increase the curing time, as they increase the required energy to initiate the curing process. In case of laboratory made resin, an exposure time for the base layer was 6 seconds, while for the rest of the layers a exposure time of 2.8 seconds was selected. The fabricated structures are shown in the figure 6.10.



(a) Fabricated structure consisting 10 µm thick layers followed by a base layer and squares of sizes 200x200, 150x150 and 100x100 pixels.



(b) Fabricated structure consisting 30 µm thick layers followed by a base layer and squares of sizes 300x300, 250x250 and 200x200 pixels.



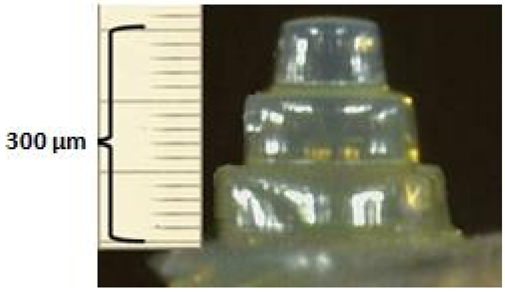
(d) Top-view of fabricated structure consisting 30 µm thick layers followed by a base layer and squares of sizes 300x300, 250x250 and 200x200 pixels.

Figure 6.10 Structures fabricated by Laboratory made resin through oxygen permeable window created by Teflon AF2400X

As, one can see that the fabrication accuracy of the parts in all of the resins is not close to few micrometers. The edges of the square are round and the entire part looks blurry. This may be because of bad focusing and unoptimized exposure time or maybe because of Teflon film since they are not completely transparent. Also, Teflon films were previously used in continuous liquid interface production but in this built setup the elevator moves after constant intervals, depending on the exposure time. So, this may also be one reason of bad accuracy of the setup.

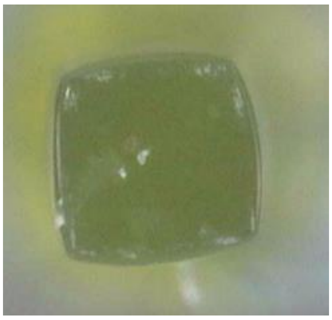
6.4.3 PDMS

In order to clarify the reason, while the fabrication accuracy is bad due to the Teflon film or because of bad focusing, a petri dish with coating of 2 mm thick PDMS was tested, to fabricate the same structures with the same exposure time as used in case of Teflon AF2400X film and the results are shown in the figures ahead.



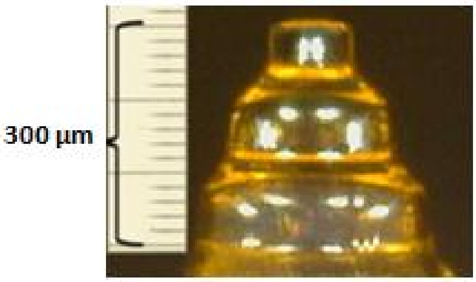
(a) Fabricated structure consisting 10 µm thick layers followed by a base layer and squares of sizes 200x200, 150x150 and 100x100 pixels.

(b) Fabricated structure consisting 30 µm thick layers followed by a base layer and squares of sizes 300x300, 250x250 and 200x200 pixels.



(c) Top-view of fabricated structure consisting 30 µm thick layers followed by a base layer and squares of sizes 300x300, 250x250 and 200x200 pixels.

Figure 6.11 Structures fabricated by HTM 140-V2 resin by using petri dish having a coating of PDMS as a resin vat.



(a) Fabricated structure consisting 10 µm thick layers followed by a base layer and squares of sizes 200x200, 150x150 and 100x100 pixels.

(b) Fabricated structure consisting 30 µm thick layers followed by a base layer and squares of sizes 300x300, 250x250 and 200x200 pixels.

(c) Top-view of fabricated structure consisting 30 µm thick layers followed by a base layer and squares of sizes 300x300, 250x250 and 200x200 pixels.

Figure 6.12 Structures fabricated by Pic-100 resin by using petri dish having a coating of PDMS as a resin vat.

(a) Fabricated structure consisting 10 µm thick layers followed by a base layer and squares of sizes 300x300, 250x250 and 200x200 pixels.

(b) Fabricated structure consisting 30 µm thick layers followed by a base layer and squares of sizes 300x300, 250x250 and 200x200 pixels.

(c) Top-view of fabricated structure consisting 30 µm thick layers followed by a base layer and squares of sizes 300x300, 250x250 and 200x200 pixels.

Figure 6.13 Structures fabricated by laboratory made resin by using petri dish having a coating of PDMS as a resin vat

The accuracy of the setup is much better in case of petri dish having a coating of PDMS than oxygen permeable window created by Teflon films. But it is still not close to few micrometers. So, this may be because of imperfect exposure time and bad focusing. Also, the resin used for fabrication process significantly affects the curing results.

As, in both of the cases (i.e. Teflon film and PDMS), the structure fabricated by laboratory made resin has better accuracy than the other two commercial resins. As, the pic-100 and HTM140-V2 are pretty dense in nature, so, when a layer is cured, there is also a possibility that some uncured or partially cured resin may stick to the edges of the cured part which later cures completely when the setup fabricates the progressive layers. Dense resins also badly affects the accuracy of the setup. A simple demonstration of this phenomenon is shown in figure 6.14.

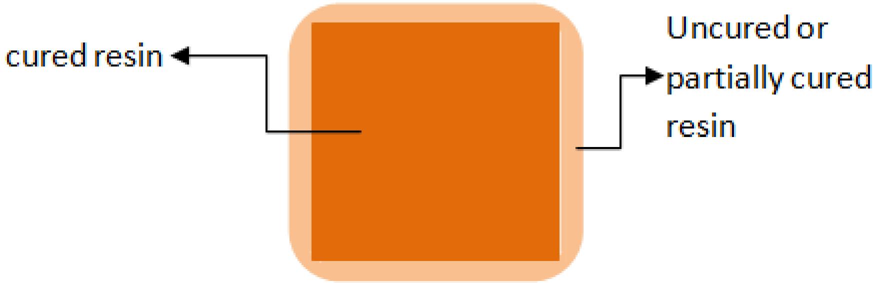
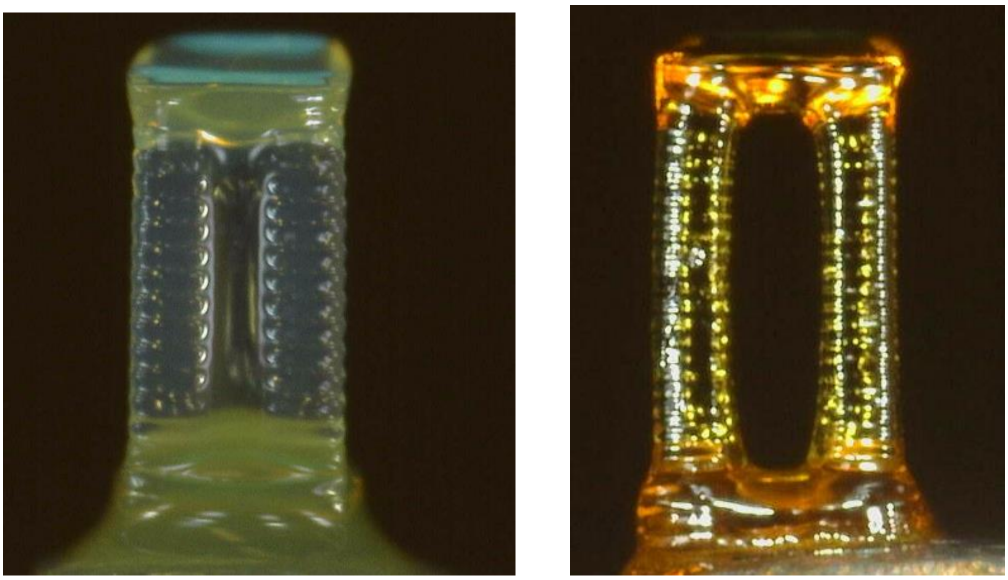


Figure 6.14 a partially or uncured resin stuck with the edges of cured part

However, from the above mentioned pictures, one can clearly verify that the layer thickness corresponds pretty well to the set value of 10 µm, showing that the platform movement and the program used to control the fabrication process operate accurately. Due to all mentioned difficulties, i.e. the dense nature of resins, errors in focusing of perfect projection and unoptimized exposure time, the manufacturing of fine-detail 3D models was postponed. However, a simple overhanging structure, having a layer thickness of 20 µm was tried to fabricate with laboratory made and HTM140-V2 resin. The results are shown in figure 6.15.



(a) Over hanging structure fabricated with HTM140-V2 resin.

(b) Over hanging structure fabricated with laboratory made resin.

Figure 6.15 Over hanging structure with layer thickness of 20 µm.

In case of vertical resolution, the print through error is quiet significant in case of HTM140-V2 resin, while the laboratory made resin performed quiet well in this case. This print through error is basically caused by over curing of the resin and it can be reduced by adding neutral absorber into the resin.

7 Summary and Conclusions

A bottom up oriented PμSL device has been built for the fabrication of three dimensional micro objects. The PμSLA consists of a LED source, a DMD to generate the desired patterns, various optical components to focus the light source on the photocurable resin, a transparent resin vat, a platform and an elevation device connected with a computer. The whole setup is controlled via computer with the help of two programs. One program is uploaded to Arduino Uno microcontroller and is used to operate the stepper motor based on commands received via serial port. While, the second program controls the fabrication process depending on the operation parameters i.e., exposure time, layer thickness, delay after and before the layer has been cured, etc.

The built setup met the requirement of lateral resolution, as the area of one pixel exposed at the bottom of resin vat was (2.65 x 2.56) μm^2. The area of one pixel was verified by curing a layer of grid of squares, see figure 6.1. While, the PμSLA can also fabricate the objects having the dimensions of up to 1 pixel, it can be verified from figure 6.2. On the other side, the programs also operated appropriately since, no issue was caused by the motor control or the projection of images. It was conclusively proved by fabricating the structures consisting of stack of layers, see figures (6.8 - 6.13).

Three different coating and three different resins were used to test the fabrication process. The tested coatings consists of a microscopic slide having coating of DIARC® Cromo, Teflon AF2400X film and a petri dish having a coating of PDMS. The DIARC® Cromo is not suitable for the manufacturing purpose since, it results in a complete manufacturing failure, showing that the adhesion strength between the cured resin and the platform is weaker than the adhesion strength between the cured resin and the coated slide, see figure 6.7.

Teflon AF2400X film has been used as an oxygen permeable window in order to create a dead zone (a thin uncured liquid layer between the film and the cured part), so that the cured part only sticks with the platform. The Teflon film served its purpose but the fabrication accuracy of the part was not close to few micrometers. The edges of fabricated squares were round and the entire part looked blurry, see figures (6.8 - 6.10). That might be because of the nature of the Teflon film, since they are not perfectly clear, or because of fabrication process, as Teflon films are previously used in continuous liquid interface production.

In order to analyze the reason, a petri dish having a thick coating of PDMS was tested later and same structures were fabricated. The accuracy of the setup was much better in case of petri dish with a coating of PDMS but it was still not close to few micrometers, see figures (6.11 - 6.13). The poor fabrication accuracy of the built setup is may be because of bad focus, resin vat, the properties of the resin and the unoptimized exposure time.

The bad focus is usually because of the used optics and their adjustment. When an object is focused using a lens system, there are always some errors between an object and a focused image. These errors can be reduced to some extent but it is impossible to remove 100% of the errors. The typical errors found in optical system are aberrations and diffractions. The aberrations are mainly due to the manufacturing defect and imperfection of lens shape or it also may arise due to different refractive index according to the wave length. The aberration does not decline the resolution of the image, but distorts it. While, diffraction refers to various phenomenon which occurs when a wave confronts any obstacle or slit. The focus can be improved by careful alignment of optics and by using more precise optics and opto-mechanics.

The resolution of fabricated parts also greatly depends on the properties of the used resin. In this research, two commercial and one laboratory made resin have been tested. The commercial resins are named as, HTM 140-V2 and Pic-100, while the laboratory made resin consists of trimethylolpropane trimethacrylate as a monomer, Lucirin TPO-L as a photoinitiator and Disperse orange 13 as a neutral absorber. One can clearly see from the figures (6.8 - 6.13), the laboratory made resins achieved better resolution and fabrication accuracy than the other two commercial resins. Since, the used commercial resins are quiet dense in nature, so as a result when a layer is cured, some uncured or partially cured resin may stick to the edges of the cured part which later cures completely when the progressive layers are fabricated, which results in huge decline of fabrication accuracy.

Besides the lateral resolution, the commercial resins also have a very bad vertical resolution. The vertical resolution basically depends on polymerized thickness of created layer. In order to observe the vertical resolution of the tested resins, a free over-hanging part has been fabricated by using HTM 140-V2 resin and a laboratory made resin, shown in figure 6.15. Since, the laboratory made resin consists of neutral absorber, it reduces the curing depth of resin resulting in better vertical resolution of the fabricated part.

Unoptimized exposure time might also be a one reason of bad accuracy of the fabrication part. Since, if the exposure time is not sufficient enough it will result in partial curing of the resin, while if the exposure time is high it will result in over curing of the resin and over curing also lowers the resolution of the fabricated part. Also, in case of high exposure time, the attachment force between the bottom of the resin vat and the cured resin layer increases and if the adhesion strength is high enough, it may results in fabrication failure or it may rips off the pieces of coating material of the resin vat. Once a pit is formed in the resin vat, the successive layers may get affected by the pit, resulting in the loss of fabrication accuracy.

Beside the above mentioned difficulties, there is also one another limitation in the built PμSL device. There is not any measuring device used for the absolute positioning of the platform. So, the platform must be lowered carefully to touch the coating in the resin vat at the beginning of the fabrication process, otherwise it may damage the coating and if the coating is damaged the resulting part will also be affected or damaged.

In conclusion, the main issue regarding to the bad fabrication accuracy seems to be the coating and the resins. So, for the future research, new resins should be developed. And as discussed before, the accuracy of the fabricated parts was better in case of PDMS. But for the research purpose, a petri dish with a thick coating (>2 mm) of PDMS was used and the bottom of the petri dish was not completely flat, which sometimes leads to unfocused curing. So, instead of a petri dish, a slide with a thin coating of the PDMS can also be used, but this gives rise to another issue that is, if the exposure time is increased, the attachment force between the bottom of the resin vat and the cured resin layer increases and if the sticking force is high enough, it may rips off the soft pieces of the PDMS every time a layer is cured resulting in the loss of shape accuracy.[14] However, PDMS may not be the only final solution for the coating material in stereolithography. LiquiGlide, which has been developed by the researchers of MIT (Massachusetts Institute of Technology), due to its super slippery and transparent nature might also be suitable for the purposes of SL. However, LiquiGlide is not yet commercially available.[32]

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