Design and Development of Control System for Selective Laser Melting Machine

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Dedicated to my exceptional father (baba), my late mother, and my wife whose tremendous support and cooperation led me to this wonderful accomplishment.

Abstract

Additive manufacturing is contrary to subtractive and formative manufacturing methodologies, the process of joining materials to make parts from 3D model data, usually by layer upon layer mechanism. Selective laser melting (SLM) technology also falls in the domain of additive manufacturing; it has a wide range of applications and is crucial in the development of high-performance and complex structural materials. It comes under the field of additive manufacturing, in which metal powders are melted and fused together with a high-power density laser. In this project, the goal was to control the mechanism related to the motion of powder deposition and layer movement. A 3-dimensional layer by layer mechanism is controlled by the Arduino-controlled stepper motor system. An interface to control both the motors is set up by using a "Processing," and this software interface is controlling the mechanism by serial communication with Arduino. Initiation of the process requires control of a layer deposition mechanism which is a z-axis-based mechanism controlled by a stepper motor and is required to step up and down the worktable for layer deposition mechanism and using motor driver by micro-stepping the required layer size is achieved. Another stepper motor is used to control the powder deposition by coupling a stepper motor to a shaft for moving an arm-connected hopper. This powder deposition mechanism is controlled and moved relative to the laser engraver's processing time. After the processing of the laser is done, the worktable will step down, and powder will be deposited and processed. The process will repeat till the completion of the part.

Key Words

Additive Manufacturing, Selective Laser Melting (SLM), Control, Arduino, Processing,

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Abbreviations

AM	Additive Manufacturing
PBF	Powder Bed Fusion
SLM	Selective Laser Melting
CAD	Computer Aided Design
LOM	Laminated Object Manufacturing
STL	Standard Tessellation Language
HAZ	Heat Affected Zone
GUI	Graphical User Interface
FDM	Fused Deposition Modeling

CHAPTER 1 INTRODUCTION

1.1 Introduction to Additive Manufacturing

Manufacturing is a process that is the phase of the transformation of material from raw form into a product ready to use. The process has to go through different steps to ensure the final product is manufactured. The steps require thorough brainstorming through the present work available in the form of literature, the design of the product, experimenting, testing and simulating the design of the product. In light of these steps, the manufacturing begins, the manufacturing process is devised and implemented.

Nowadays, 3D printing has gained attention because of its green manufacturing technique, which was earlier known as rapid Prototyping and now additive manufacturing. Additive manufacturing is a process of layer-by-layer building of the part; it is getting more and more attention because of its fulfilling with the performance demand required by the custom product market, as precise work is required for the intricate part with complex functionalities. The process of additive manufacturing simplifies the process of manufacturing complex parts with CAD data. The tools, moulds and fixtures contrary to subtractive and formative manufacturing are not required in this; additive manufacturing offers eco-friendly green manufacturing, which benefits the environment in the form of reduced energy use, lesser material wastage, and efficient production. Like the aerospace industry, automobile, medical and defence sectors require customized products, the role of additive manufacturing has gained immense importance in the last three decades. In recent, it has impacted beyond R&D fields, and its applications are covering every custom product-based market. The principle for every additive manufacturing process is that a CAD-based digital model is transformed with the addition of layer over layer with time till a three-dimensional physical product is built.

It is a completely different mechanism to the traditional manufacturing processes like CNC machining and Injection moulding. As an alternative to subtractive and formative manufacturing technologies, specific tools and moulds are not required. In fact, the material is just processed, and part is directly manufactured over the built worktable in layer-by-layer form. And it all starts with the CAD three-dimensional model designed, and the model is sliced by the software into a two-dimensional format. Then the set of instructions are defined for the Printer to manufacture the part.

1.1.1. BENEFITS OF ADDITIVE MANUFACTURING:

- The most apparent result for those that approach AM is achieving the goal of manufacturing highly intricate and specific shapes. It helps in fabricating parts that cannot be brought in form with subtractive manufacturing because of limitations.
- It is evident that a manufacturing process in which increasing complexity does not lead to a rise in cost finds is an opportunity for application areas that demand a high degree of customization of features, such as biomedical, automotive and aerospace.
- Another characteristic, which helps to make AM especially attractive, concerns its high eco-sustainability, related both to the manufacturing process itself - due to the option of recycling the surplus powder - and to the performance in the use of the components.
- As far as Automotive and Aerospace are concerned, the design of components according to the design for additive paradigm allows to reduce the amount of material used and, therefore, the final weight.
- Compared to traditional manufacturing processes, the reduced energy is also in favour of cost- sustainability.

1.2 Problem Statement

The desire of every manufacturing industry is to achieve minimum lead time with the qualitative product and is considered a trademark of success. The processes with minimal lead time are preferred over the ones demanding more time. The efforts are always in the direction to reduce lead time for the competition to meet in the market. In metal processing, the traditional ways are subtractive and formative. Though CNC's are more robust than past, still it takes hours and days to manufacture the part depending upon the complexity of its geometry. And in some cases, the subtractive manufacturing technology is not able to completely manufacture the part.

In this era, the choice of additive manufacturing can be considered the optimum solution for the industry in terms of their desired lead time. The process is the joining of material to create parts designed in the form of 3D model data. Additive manufacturing, also known as Rapid Prototyping, can be used for metal printing. For processing the complex structure in metal parts, additive manufacturing is quite suitable. The methods used in metal processing are Selective laser sintering, selective laser melting and Direct energy deposition. The Powder Bed fusion-based processes like SLM and SLS requires process parameter study, and the evaluation of parameters like relative density, porosity, surface roughness, and dimensional accuracy are studied according to the interaction impact of the process parameters (Maamoun et al., 2018). The variety of metal powders are used, and the size of powder distribution and powder are studied relative to the melt pool (Zelinski et al., 2017). Additive manufacturing provides quality results, and the built part qualitatively has optimum metal properties.

The potential of enabling custom products for the specific market is of immense significance as it has dominant advantages over the traditional market, as the manufacturing of complex and intricate customized parts with minimum lead time and less wastage of material. Thus customized products industry like aerospace, automobile, medical and defence sector has adopted the additive manufacturing on a commercial scale in last two decades. The study and work in the SLM have advanced in the last five years, with solutions for precise layer thickness for better resolution, the correlation of temperature distribution and melt pool size, and the study of laser process parameters. The room for better resolution of the part which directs to the precise and smaller layer thickness will always be there.

1.3 Objectives

The primary objective of this project is to modify a laser engraving machine into a prototype of metal 3D Printing Selective Laser Melting machine for implementing a layer-by-layer mechanism on metal. This requires designing and control of the SLM machine. These are the objectives of this study that are catered to in this thesis.

- To Study the methods currently in the process of additive manufacturing and layer by layer deposition mechanisms.
- To Study the literature related to the design and control of additive manufacturing processes and the process parameters.
- To design the mechanism for XY control for deposition of powder layer and Z-axis (vertical) mechanism of worktable for control of layer thickness.
- To design and develop a control for the mechanisms of deposition and Z-axis mechanism
- To make a GUI for controlling the mechanism for a user interface on the computer.
- To identify and suggest future work.

1.4 Breakdown for the thesis report:

This thesis report consists of five chapters. The first chapter includes the Introduction of manufacturing and additive manufacturing, the problem, and the objectives of the project. The second chapter covers the literature review related to and required during the process of research. The third chapter is regarding the design and development of the Selective laser melting machine. The fourth chapter is about the design and development of control of the project. The fifth chapter covers the conclusion and future recommendations.

CHAPTER 2 LITERATURE REVIEW

2.1ADDITIVE MANUFACTURING:

Rapid Prototyping, 3D Printing and Additive Manufacturing all these phrases refers to a process to create a three-dimensional part or assembly by layer-by-layer depositing of the material rather than subtracting the material from the material, using computer-aided design data. The model data is cut into layers in sequence. After that, these layers are deposited sequentially by the process of the specific type of additive manufacturing which leads to the creation of a three-dimensional part of the required geometrical data.

There has been development in additive manufacturing, and various types of processes are developed with the goal of different types of material part printing. The processes that are widely used are mentioned below:

2.2ADDITIVE MANUFACTURING PROCESS TYPES:

2.2.1. STEREOLITHOGRAPHY:

It is a laser-based method that uses UV-light to cure or harden the resin relative to the two-dimensional layer of the part and after the processing is done. For this process, a photosensitive polymer resin is used, which is a controlled setting; a vat filled with photopolymer resin is exposed to UV radiation and gets the resin hardened. The platform moves the processed layer downward, and after that, a new layer is hardened by VAT photopolymerization. This step is carried out till the part is completely built.

Stereolithography is used to construct layer by layer objects. Resins are polymer compounds that include additives for purposes such as Tough, Flexible, Dental, and so on. These procedures give the item a high-quality surface finish. SLA AND Digital Light Processing are the most prevalent processes in this area (DLP). In fig. 1, the process of SLA is shown.

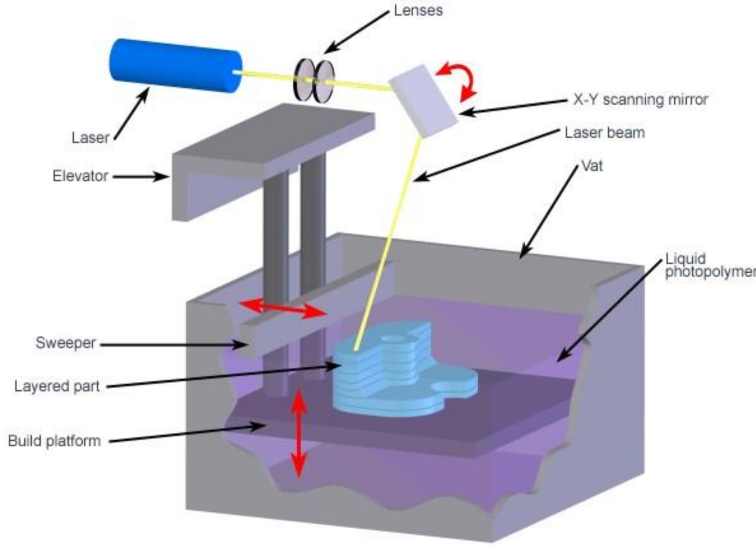

Figure 1 The Process of Stereolithography

2.2.2. Binder Jetting:

This technique works via the use of specific solidifying agents, which is why it is named Inkjet Printing, owing to the resemblance with the ink of ordinary printers. In particular, this technique allows for selectively hardening successive layers of powder by adding solidifying chemicals. The powders consist of the structural material plus a binder which may be organic or inorganic. This kind of processing enables you to work without the use of heat but needs heat treatment for the metal components to decrease the proportion of binder and therefore get superior structural characteristics. However, it is essential to take into consideration in the design phase the removal of the components if exposed to this treatment since it is highly emphasized. Particles in polymer, metal but also in ceramic or glass may be manufactured with great productivity. The details, particularly those in polymer, may be produced in a wide variety of colours.

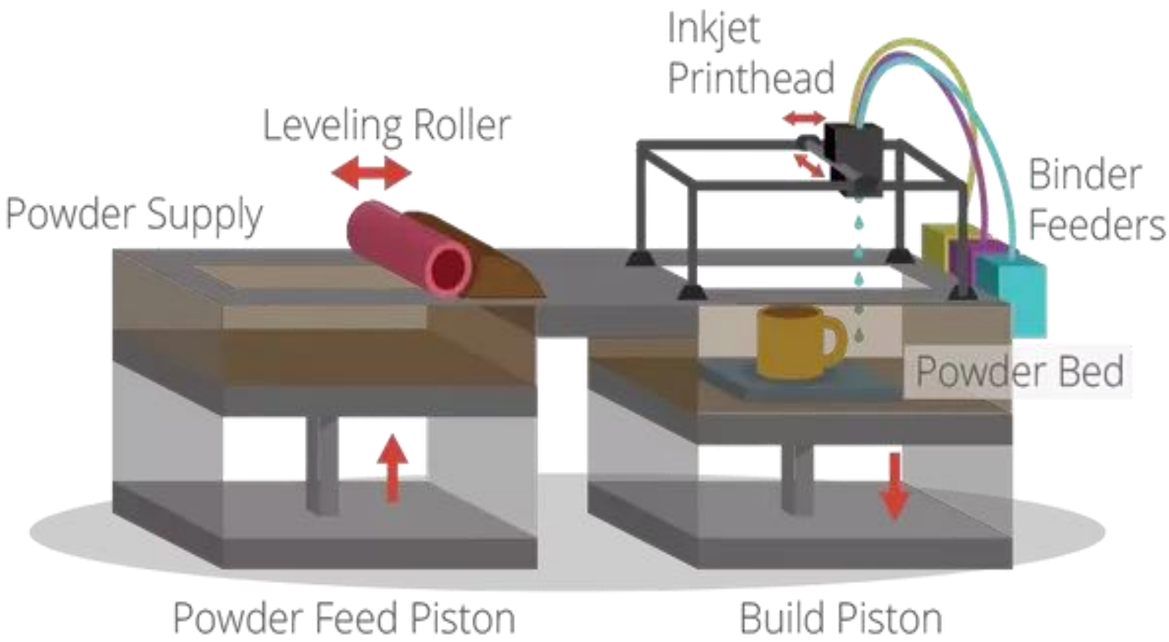

Figure 2 The process of Binder Jetting

2.2.3. FUSED DEPOSITION MODELING:

It is the most well-known printing technique, in which heated material is ejected via a nozzle and onto a build plate. This process is also known as metal extrusion, which in fact, is a process to extrude the material. The heated nozzle moves around by extruding the material in a filament shape at a specific position where the material is deposited, and the heated material hardens according to fig. 3. The same layer by layer process is carried out to completely form the part. The nozzle moves in two dimensions for the layer deposition of material by the nozzle, while the build platform is moved down a step in Z-axis for the next layer till the part is completed. The components may be printed with similar precision in both glossy and matte finishes. It is a multi-material printing technique that allows for full-colour printing.

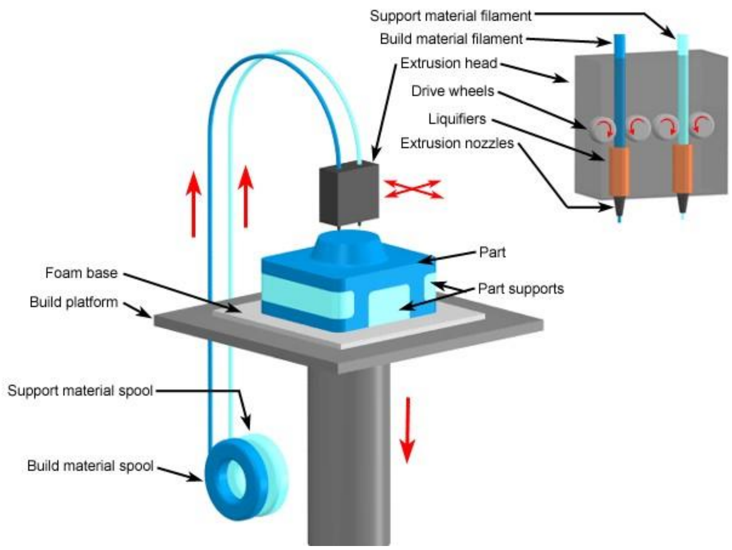

Figure 3 The process of Fused deposition modelling

2.2.4. LAMINATED OBJECT MANUFACTURING:

Several sheets of material are layered and bonded together to create the desired product. The lamination of the sheets, cut with a blade or by laser, may be done chemically by means of adhesives, ultrasonic welding or brazing (only for metals) (only for metals). The pieces that are sliced layer by layer are eliminated at the conclusion of the procedure. This technique enables great production at relatively low prices, and it also allows you to build things with components embedded in the sheets. Objects may be obtained by working sheets of paper, plastic and metals.

2.2.5. Direct Energy Deposition/ Laser Cladding:

This type of processing adds material to existing solids; it is, therefore, possible to carry out repairs or additions of one or more different materials and can be combined with processes such as laser cutting or milling. In this type of processing, a laser or an electron source increases the local temperature of the point on which it is necessary to work, generating a molten bath on which the wire or powder brought by the processing nozzle will melt. Welding beads are then created, which will form the desired geometry by overlapping each other. The processing point is often flooded with inert gas to avoid oxidation or other reactions of the locally melted material. Given its peculiarities, this technology allows a rapid passage from one material to another (just switch to a different powder or thread) and a large contribution of volumetric construction when compared with other additive technologies.

2.2.6. Powder Bed Fusion (PBF):

It is presently the most promising technique for the additive manufacture of metals since it enables the fabrication of high-performance structural components. The method is relatively basic as layers of metal powders are afterwards solidified by a laser beam guided by moving mirrors. The precision casting triggered by the laser yields a highly homogeneous material, and it is for this reason that the characteristics of the alloys treated in this manner are even better than those processed by mechanical technologies. Many metal alloys can be worked from aluminium to titanium with complicated geometries, but the machines operate on extremely tiny surfaces and with very high prices. This project falls under the powder bed fusion type, as a metal powder will be required to be processed by a modified laser machine, as shown in fig. 4. This will require a system for depositing metal powder on the worktable with the help of an arm-hopper mechanism controlled by a coupled actuator. Similarly, a Z-axis mechanism will be developed for the control of layer thickness of the metal powder deposited onto the worktable and during the processing of stepping down the build platform.

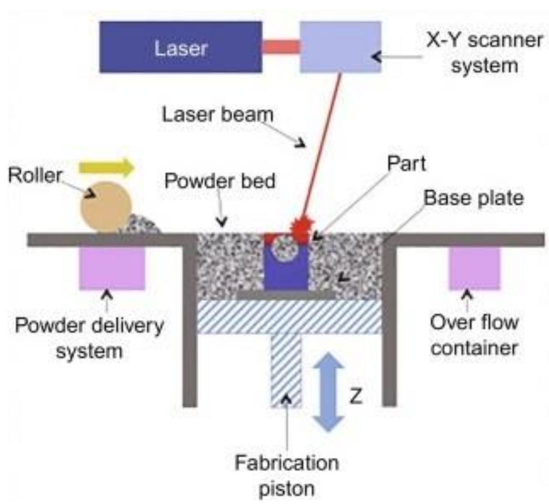

Figure 4 Process for PBF

2.3 Steps for additive manufacturing:

2.3.1. CAD:

Creating a digital model is the first step in the additive manufacturing process. The most common method used today to create this type of file is CAD (Computer-Aided Drafting, translated "Computer Aided Technical Drawing"). There are many free and professional CAD software compatible with 3D printing. Reverse engineering can be a good alternative and a valid tool for creating a 3D model via 3D scanning.

In the first step of 3D printing, a part of the 3D CAD model is required to be designed. For which there is a variety of professional CAD software, which are compatible with 3D printing. An alternative of 3D scanning the part physically and creating a model is also a reverse engineering alternative. Different ways of conceiving the model for additive manufacturing need to be evaluated. These focus mainly on the geometry of the piece and the need for supports to correctly print the object, which varies according to the type of technology adopted.

2.3.2. STL conversion and file modification:

Conversion of the CAD file to STL is an important step of the process. STL defines the surface of an object consisting of triangles (polygons). For converting the 3D model into a printable file, it is necessary to take into account the physical size of the object, the number of polygons that constitute it and its rigidity. Once the file is generated, it can be imported into a Slicer (open-source software platform), where the data will be stored.

2.3.3. 3D Printer Setting:

The STL file will be transferred to the respective 3D Printer mostly via USB. So the file is transferred accordingly. The machine parameters like support and time will be set according to the respective machine's available manual.

2.3.4. Removing the supports:

In some cases of removing the supports is as easy as if removing the printed part from the platform. But in some 3D printing methods, the removal becomes quite technical, as it requires a precise separating technique for the part from support. That requires a qualified technical individual to safely remove the supports.

2.3.5. Post-production phase:

After the removal of supports, the product is almost ready for application, but the quality variance in different techniques of the Printer requires post-processing on the part. Most materials can be sanded and cleaned with compressed air and coated for protection. Some parts require retouching or post-curing.

2.4. Metal Additive Manufacturing

For any additive manufacturing, two parameters that are considered of great importance are the source of energy and material used for the product. Metal additive manufacturing as a tool-less technique requires an energy source, which is a laser. Materials used in the process are in the form of powder. From the formation of CAD file to its conversion to STL file, and for building a complete product, there are many factors. This is a form of solid freeform fabrication which encapsulates all the additive manufacturing processes.

Metal additive manufacturing constitutes two types:

- Direct Energy Deposition
- Powder bed fusion

The mechanical characteristics of laser direct energy deposition and powder bed fusion were examined on Iron-Cobalt alloy material showed an enhanced strength and improved ductility of the material (Babuska et al., 2021). There are many factors impacting metal additive manufacturing; there is particle Size Distribution (PSD) indicates the frequency of particle size in a sample of powder material. PSD influences the key powder properties of flowability and compaction. Thermal conductivity, melting point, evaporation point, density and viscosity are the parameters that are associated with the metal powder material.

The following figure 5 shows the different types of processes of additive manufacturing with PBF processes highlighted.

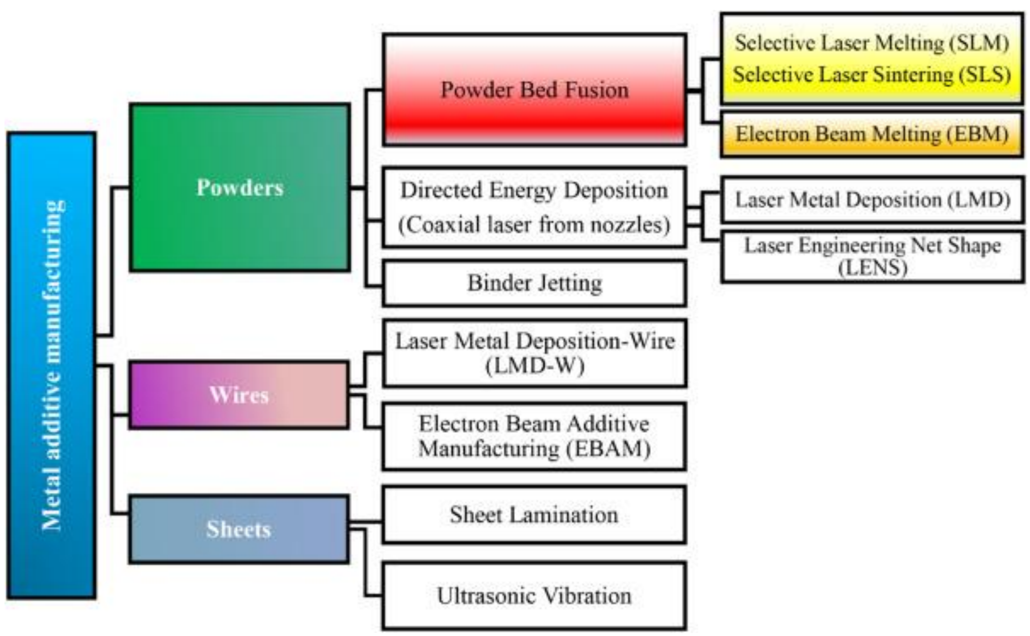

Figure 5 The types of additive manufacturing

2.4.1. POWDER BED FUSION:

Powder Bed Fusion is a process that comes under energy use-based processes. In this laser, energy is used to process the metal powder material. Different metals are used to manufacture parts for different engineering and industrial applications. Many metal alloys have been used in manufacturing medical implants because of their biocompatibility.

Selective Laser Sintering was amongst the first methods adopted to be implemented under the PBF. The approach of all powder bed fusion processes is similar relative to the material and required part. As mentioned earlier, an energy source is required to heat the metal powder so it melts and the selected area is processed. The process requires a controlled environment and control for build a platform for layer thickness. Besides that, control of powder deposition is also required. The energy source used normally in the PBF is a laser. The temperature plays an important factor as metal powder requires pre-heating before exposure to the laser. In earlier PBF systems, the powder deposition mechanism used the roller for levelling the metal powder, and in an enclosed box, the processing is done. Which is filled with inert gas (mostly Argon or Nitrogen), so the oxidation does not occur inside the box. The laser focus is controlled by pre-defined code, processing on the specific portion of metal powder is done. Then the platform is brought a step-down for the laser processing on another layer, and this keeps on till part is built up. The part is removed for further post-processing.

2.5 SELECTIVE LASER MELTING:

2.5.1. COMMERCIAL SLM MACHINE

The advancement in the area of metal 3D printing utilizing the additive manufacturing processes over the past decade, and there are commercially developed SLM machines from companies like SLM-Solutions. Their presence in the market is evidence of their relatability in the market. These machines are quite expensive, but they are the way forward for processing metal in a precise and accurate manner. Table 1 displays the technical specifications of a commercial SLM printer made by SLM-Solutions.

Figure 6 Commercial SLM machine SLM-100 by SLM-Solutions

Technical Specifications	
Build Envelope (L x W x H)	125 x 125 x 125 mm
Build Volume Reduction (L x W x H)	50 x 50 x 50 mm
3D Optics Configuration	Single (1x 400 W) IPG fiber laser
Real Build Rate	20 µm - 75 µm, more available on
Variable Layer Thickness	On request
Beam Focus Diameter	70 µm - 100 µm
Maximum Scan Speed	10 m/s
Average Inert Gas Consumption in Process	0.6 I/min (Argon)
E-Connection / Power Input	400 Volt 3NPE, 32 A, 50/60 Hz, 3 kW
Machine Dimensions (L x W x H)	1400 mm x 900 mm x 2460 mm

Table 1 Specifications of the commercial SLM

2.5.2. INTRODUCTION TO SLM:

In SLM, metal particles are completely melted to create a solid component, and no additional post-processing is needed in the furnace. Different process parameters are modified to produce completely dense, straight to use metal components. In principle, all metals or metal alloys might be treated by SLM; however, the spectrum of commercially accessible metals for SLM is still restricted today. This is because the ease of processing varies a lot according to the physical characteristics of the materials, e.g. thermal expansion coefficient, melting point, thermal conductivity, surface tension, laser absorption and viscosity etc.

Direct metal laser fabrication includes the process of Selective laser melting as the metal powders are fully melted for the formation of a solid part. The physical characteristics of the materials, i.e. melting point, thermal conductivity, surface tension, viscosity and heat source absorption, impact and restricts the choice of material selection for SLM. A few of the materials being utilized in this method may include Ni-based super alloys, copper, aluminium, stainless steel, tool steel, cobalt chrome, titanium and tungsten (tan et al., 2018). SLM is particularly helpful for manufacturing tungsten components due to the high melting point and high ductile-brittle transition temperature of this metal. SLM is a technique where the laser is used to process the metal powder; as it comes under the powder bed fusion method, the metal powder is spread on the bed. The laser beam is directed on pre-specified areas according to the CAD model to completely melt the powder. This process is carried on till all the layers required to complete a part are processed. In Selective laser sintering, the same process of the layer-by-layer mechanism takes place, but in SLM, more laser power is used to melt the powder, while in the case of SLS, the powder is sintered. SLS is more often applied to materials such as plastics, glass, ceramics, and as well as metal. What makes SLM different is its ability to completely melt the powder rather than sinter (where the powder is heated to a certain degree that the powder grains may fuse together). In the case of SLM, the powder is liquified by utilizing laser power till the powder grains are homogenous. That ensures much strength a reduced porosity, and optimum crystal structure.

As an additive manufacturing technique for metals, SLM helps in the creation of customized three-dimensional Structures with unprecedented degrees of freedom. Development in the field is quickly taking place, and promising findings are opening for a variety of new applications. Both in industrial and engineering areas, the benefits can be witnessed. The industries are making possible the fabrication of complex metal parts using SLM for gaining the objective of light weight, better functionality and better-finished part. Decreased design-to-manufacture time and decreased cost are also the benefits that attract the industry to adopt new techniques

(Aboulkhair, 2019).

The process includes melting of the metal powder using laser as an energy source, and then quickly solidification is required for the molten material to shape according to the required part. There is a number of steps involved, from modelling the CAD model to desired finished part. Like other additive manufacturing processes, a CAD file is transformed.STL file. A thin coating layer of fine metal powder is uniformly laid on the build platform with the help of a powder deposition mechanism. After which a high energy laser is used for processing the powder, the layer of powder gets melt and fused on a specific area according to the CAD model and sliced data. This is done using a high-power laser beam, typically a ytterbium fiber laser. Here the scanning of a layer is completed, the build platform is indexed down, travelling in a Z-axis vertically, with the next layer placed on the processed powder and scanning of another layer takes place. This loop is carried on till the complete construction of the part. The laser beam is focused in the X and Y directions using two high-frequency scanning mirrors. The laser energy is strong enough to enable the complete melting of each layer. After the laser scanning and completion of the steps, the part is removed by the build platform. Besides, if post-processing or re-processing is required, the part is processed accordingly. For the process, the chamber where the process of laser processing is taking place needs to be filled with inert gas, so the material is protected as oxidation can contaminate the molten metal. During the SLM process, an inert gas is pumped into the build chamber to produce an inert environment and to transport undesirable process by-products away from the laser beam and powder bed.

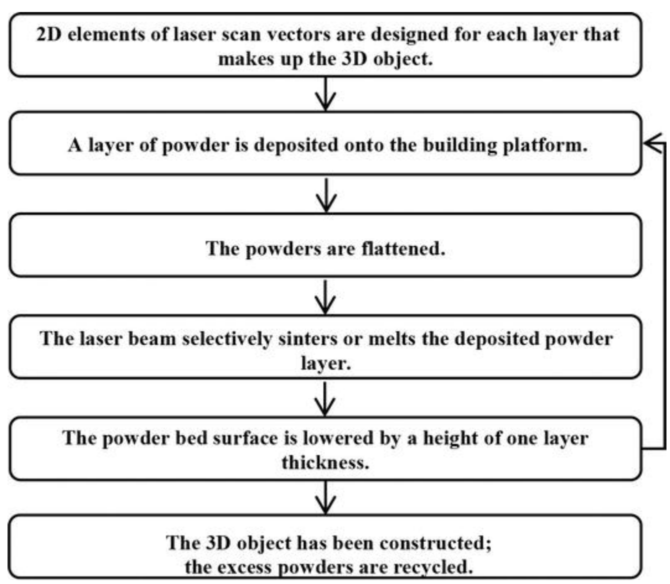

Figure 7 Steps involved in the process of SLM process

The SLM, in some cases, can provide the pre-heating of the build platform or the whole chamber. The parts manufactured with the pre-heating technique have a homogenous microstructure and better material properties; they have better mechanical properties than the not pre-heated and even parts processed with conventional processes. The UTS (ultimate tensile strength) is like the conventionally produced parts (Mertens et al., 2016). This shows that the pre-heating applied to the SLM process can reduce the post-processing requirement for the part, which will reduce the manufacturing time and cost.

Achieving excellent mechanical characteristics with the accurate dimensional part and better surface quality of SLM processed components with minimum post-processing are important in the field of metal 3D Printing. The findings show that minimal layer thickness the denseness will be the part, and excellent dimensional accuracy will be obtained. With optimization of process parameters, the increased mechanical properties and micro hardness were also achieved (Nguyen et al., 2018). Finer the powder particle size is, the finer resolution and good powder flowability will be attained.

2.5.3. APPLICATIONS OF SLM:

Many SLM metal materials have applications depending upon the characteristics like hardness, ductile nature, and other mechanical properties as the technique is costly with respect to conventional production processes. The applications are in value-added areas like automobile, pharmaceuticals, aerospace, and industrial tooling. In medical like dental uses of SLM requires no customization cost, and a functioning part is produced easily. A biocompatible metal structure for dental prostheses is developed with the help of SLM (Kruth et al., 2005). Premolar and molar dental crowns with gold were efficiently produced utilizing the SLM technique (Khan et al., 2014).

In the aerospace and automobile industry, the research is highly concentrated on performance at high temperatures and more lightweight part-based work. The utilization of nickel-based super alloy, a composite material cermet to investigate the Selective Laser Melting manufacture of abrasive turbine blade tips to reduce leakage of gas and enhanced productivity of gas turbines is studied(Yap et al., 2015). Product design for the high-quality prototypes required are achievable with SLM with a shorter design cycle and is practised. Due to the complex structure of production systems, the technical potential of AM and particularly SLM can only be achieved through a comprehensive understanding of the entire value creation chain, notably the interdependency between products and production processes.

2.6 PROCESS PARAMETERS:

The process parameters affecting the process of selective laser melting are numerous and interconnected; these can be categorized into three basic categories looking at the processes taking place in the SLM.

1. Material based Parameters
2. Laser-based Parameters
3. Scan based Parameters.
4. Environmental Parameters.

2.6.1 Material base Parameters:

The material selection for processing among the metal powders depends upon the material properties. These variables are fixed, including melting point, latent heat of fusion, heat capacity, density, and particle-sized distribution. During laser processing, the interaction with material brings other stakes coming into play, like heat transfer in the build platform where the powder is deposited. The radiation absorption and the dependence on the phase of material also matters. All these factors are linked with each other. Laser power must be adjusted for every other material because of absorptivity of materials, which will be different for every material because of material's size, density, powder form, powder compaction, materials melting temperature, powder bed temperature. Layer thickness is an important parameter that highly impacts the quality of parts manufactured.

2.6.2 laser-based Parameters:

SLM is using laser as an energy source to thermally energize the powder to melt it; the thermal property of laser and its interaction with powder is significant. The parameters like the wavelength of the laser, the mode, the power, spot size and pulse duration are the parameters important to study the process. The factors of wavelength, pulse rate, duration and power influence the melting and solidification phases of SLM, which ultimately impacts the quality of parts. The setting of the laser needs to be adjusted with respect to the material used for attaining the best result in terms of scanning and part quality. In Selective laser melting, Nd:YAG and Yb-fiber lasers are preferred over CO2 lasers because of its better beam quality results in higher dimensional accuracy and high-quality part. As metal powder has higher absorptivity at a shorter wavelength, so fibre lasers are favoured over others.

2.6.3 Scan based Parameters:

The scan speed, hatch spacing, and scan pattern are the parameters that impact the SLM process. These parameters ensure that the layer scanned by laser beam has a positive impact on the processing of layer, time to process, surface roughness and mechanical quality of the component.

The speed with which the scanning is done on the layer of metal powder, how fast the scan is done affects the quality of parts and productivity of the process. The hatch spacing or scan spacing is the separation between two consecutive scan patterns. It is calculated by the distance between the centre of one laser beam to the other center. The scan spacing is directly effecting the build productivity; it enhances layer integrity and reduces porosity.

The scan strategy helps in the reduction of stresses on the components. The uni-directional scanning strategy with contour style (stripe) where the uni-directional scanning pattern followed by the contour scanning style exhibited the finest grain size and greatest yield strength (Chen et al., 2005). The contour-based scanning shows enhanced mechanical characteristics and quality products (Biffi et al., 2020). The parameters that are adjustable are laser power, scan speed and hatch spacing in a laser-based system. These three parameters play an important role in the transfer of laser energy to the material. The combination of high-power laser and low scanning speed helps in avoiding balling; balling occurs because of surface tension and less processing of last layer processed by laser.

2.6.4 environment based parameters:

During the laser processing inside the chamber of SLM setup, the control of the atmosphere is crucial, as the oxygen present inside can oxidize the metal powder. In SLM, the inert gas flow is required to control the oxidation, so the contamination of parts can be minimized. Selecting gas is crucial because the flow rate, flow direction and the type of gas effects the quality of the build part, its microstructure, porosity, and that directly affect the mechanical properties of the part produced. The temperature control inside the chamber is an important parameter; the control of powder bed temperature is also very important because if the temperature of the powder bed is higher, the thermal gradient between phases of the metal powder will lessen the thermal stresses. Most of the metals require temperature control. For controlling the contamination, inert gases, mostly Argon or Nitrogen, are introduced into the chamber as there are thermal properties involved in processing metal powder with a high-intensity laser beam and then solidification of processed molten powder at room temperature. The fast-cooling leads to the formation of fine microstructures inside the melt pool. The portion of the grains makes the melt pool, which in the core is equiaxed grains, and the outer boundary is with coarser columnar grains and HAZ. The border grains develop along the temperature slope. The directionality also creates a material with variation adjustable by the scan pattern applied during processing. This improves the mechanical properties.

2.6.5 Energy density and its relation with material properties:

Laser power, scanning speed, hatch spacing, and powder bed layer thickness are some of the most important variables that are involved in the SLM process. These parameters need to be modified for each material to guarantee a successful production. The process parameters directly affect the morphology, porosity, mechanical properties, hardness, and surface quality of the final product. The combination of these properties is represented as the energy density $(E = P/Vh)\ \frac{J}{mm^2}$, this equation represents the amount of energy absorbed by a unit volume of the material.

The Laser Energy density (E), Laser Power (p), Scanning Speed (v) and hatch spacing (h) are the variable which involves the calculation of the amount of energy absorbed, with the addition of layer thickness (t) for the volumetric energy density of the laser.

$$E = \frac{p}{vht}$$

The three factors typically work together to transmit laser energy to the powder bed. For example, if the absorption coefficient is not particularly high, it may be adjusted by changing one or all of the three values (Zhang et al., 2018). High laser power and low scanning speed is a combination that reduces the occurrence of balling phenomenon (Li et al., 2012). For qualitatively better and defect-less parts, the parameters should be adjusted for each material. In addition to having a dense part, the structural and functional thermomechanical properties of the produced components are important.

2.7 Laser:

The term "Laser" is an abbreviation for "Light Amplification by Stimulated Emission of Radiation". They are electromagnetic waves; they differ from the light source in an unattainable high intensity, the power, with outstanding monochromaticity with containing single wavelength, with the sharp focus of the beam, and wide frequency range. The coherence length and its extremely short and intense beam pulses, all waves in the beam in phase, makes it different.

2.7.1 Properties of Laser:

1. Laser Beam Power:

Laser Power is the decisive parameter in the processing quality of melting the powder. Power mainly is the main feature of a laser varying in different wattages. Power means the delivery of energy with respect to time. The variance in pulsed wave laser is because of the time variation that can be calculated by average power. The power applied upon unit area is the intensity which is another way to describe the power.

2. Wavelength:

A laser creates a beam of very strong light. The fundamental difference between laser light and light generated by white light sources (such as a light bulb) is that laser light is monochromatic, directed and coherent. Monochromatic implies that all of the light generated by the laser is of a single wavelength. White light is a mixture of all visible wavelengths (400 - 700 nm). Directional indicates that the beam of light has very minimal divergence. The material of the laser selects the range of output wavelengths, and the optics employed determines the laser wavelength which should be emitted. Lasers are most often employed in the spectrum of visible, ultraviolet, and infrared parts.

3. Coherence:

Stimulated emission makes laser light coherent because output photons have the same wavelength and phase as the input photons that stimulate emission.

The degree of coherence hinges on the spectrum of wavelengths emitted, which varies among lasers. A laser that generates just a single wavelength, called monochromatic, generally is more coherent than a laser emitting a wider variety of colours. Monochromatic light need not be coherent, but the light that is not monochromatic cannot stay coherent over a long distance. Lasers are the only light sources that can readily generate light that is coherent over relatively large distances of centimetres and above.

4. Divergence:

It is the spread of the beam at a small angle; it depends upon the type of laser and on the optical instrument used. The laser optics are used to focus the beam and concentrate on the desired point. Divergence is very small. It is measured in milliradians.

5. Laser Variation time:

The pulse duration is the variation of the pulse by turning on and off, modulating the beam. In a continuous laser, the time can be controlled for the benefit. The pulse time varies in different laser types, but it can also be controlled and varied by the user. One method is the modulation of laser input power. Secondly, it can be maneuvered with the help of optical instruments.

2.8 Modes of Operation:

2.8.1. Continuous Wave Laser:

Continuous-wave lasers have a nominally constant output over a specified interval. This means that key beam parameters (power output, intensity, etc.) remain constant throughout the beam's lifespan. The term continuous-wave refers to the coherent beam of monochromatic light generated by the gain medium, which also specifies the laser wavelength. That first solid-state laser used a synthetic ruby to produce visible light with a deep red colour, corresponding to a wavelength of approximately 694 nanometres (nm).

Many continuous-wave lasers today still use crystal gain media. Titanium-sapphire, or Ti:Sapphire, and neodymium-doped yttrium aluminium garnet (Nd:YAG) are among the most typical gain crystals for continuous-wave systems. But intensive research and development over the years have also created a variety of gas and fiber lasers, extending the reach of continuous-wave lasers significantly.

2.8.2. Pulsed Wave Laser:

Pulsed lasers are lasers that generate light not in a continuous way but rather in the form of optical pulses (light bursts). The term is most commonly used for Q-switched lasers, which typically generate nanosecond pulses, but this article offers an overview of a wider range of pulse-generating lasers. Depending on the pulse duration, pulse energy, pulse repetition rate and wavelength required, many different methods for pulse generation and many varied types of pulsed lasers are used.

A pulse laser utilizes short bursts of energy to melt the material, and the melt pool produced is maintained molten by repeated pulses. A pulsed laser scans a straight line by numerous overlapping patches of these molten zones, which are also visible in the overlapped solidified material. The pulse laser system usually has additional parameters to regulate, such as pulse energy, pulse duration, repetition rate (which allows for a wider variety of experimental circumstances) and energy control. This assists in fine adjusting the experimental parameters for better outcomes.

2.9 Parameters and specifications of Laser engraver:

In the case of SLM, the laser is utilized as an energy source; in fact, it is used in most additive manufacturing processes like L-PBF and SLA. The laser emits light that is coherent, and that is the reason for its application in laser cutting, welding and other layer by layer mechanisms. The focus of beams makes sure that the power is concentrated on a particular area.

In additive manufacturing, laser as an application is used in many processes, and the reason is the high-density power and coherent beam and its maneuverability with the use of lenses. It is used in stereolithography for the curing of photopolymer resins. Other than that, the metal powder in the PBF process is exposed to the laser, and it is processed by the thermal energy of the laser, which requires control over the process as varying the solidification can affect the part quality.

The laser engraver used in the project has a Yb - fiber laser; the machine is capable of continuous and pulse mode. The physical properties like laser frequency, speed and power can be varied. These are the specifications of the KUNTAI desktop fiber laser engraving machine.

Laser Type	Fiber Laser
Power Output	20 watts
Marking Area	175 mm x 175mm
Wavelength	1064 ±10 nm
Cooling	Air Cooled
Marking Speed	Less than or Equals to 9000 mm/s
Frequency	20 kHz to 100 kHz
Marking Depth	Less than or Equals to 0.1 mm
Operation Temperature	10-35°C

Table 2 Specification for the laser engraver machine

CHAPTER 3 DESIGN AND DEVELOPMENT

The main idea of the project was the development of an inexpensive non-commercial prototype of a Selective Laser melting machine. As mentioned in the literature review that the additive manufacturing technique based commercial SLM machines are way expensive. Contrary to that, a powder bed fusion-based mechanism for metal 3D printing was decided to model, develop, and experiment on. The design mechanism required in SLM is based on two functions of the process. First is the powder deposition mechanism, and the other is for the vertical (Z-axis) mechanism for controlling the layer thickness and stepping down of the worktable for the next layer of material. Besides, a chamber or a box is required for the assembling of and powder deposition and the enclosed box for processing of laser. The powder deposition mechanism and Z-axis motion for the powder bed or worktable requires an actuator for controlling the mechanism in the desired manner. The design for assembly is followed, keeping in mind the requirement of the prototypic nature of the machine, which frequently requires assembly and disassembling of the different parts of the unit. Other than that reduction of cost, the complexity and the parts for the assembly was thought of during the designing phase.

The initial stage of any process of manufacturing is designing the model of the component or product that is required. In this project, designing the CAD models were done on PTC Creo 3.0. The parts decided were fabricated on a CNC machine in the Department of Design and manufacturing of NUST.

The material used for fabrication was Aluminum, as during the selection of material because of better surface quality with less surface roughness required for the powder bed and light weight of Aluminum contrary to mild steel and HSS. Acrylic was also considered, but the heat resistance improved strength considered to an acrylic sheet, and affordability made it a better choice to opt for.

3.1 DESIGNING OF SLM:

The design is divided into four parts:

1. Design of Powder deposition mechanism.
2. Design of vertical (Z-axis) for build platform.
3. Design of Chamber for SLM.
4. Design of base frame.

3.1.1 Design of Powder deposition mechanism:

This assembly, coupled with the stepper motor, will be responsible for depositing the powder layers across the desired surface. This assembly movement will be controlled by a stepper motor which will be operated through limit switches. Limit switches are contact sensors that are physically or mechanically activated. The lever in the mechanism in case of contact triggers a signal. The limit switches are mounted on the inner walls of the chamber parallel to the hopper sides. The position of limit switches can be seen in fig. 9.

The powder deposition mechanism consists of a container or hopper for the metal powder, earlier manufactured with plastic by SLA. But the part ultimately was fabricated using Aluminum plates. The arm is designed to attach with the hopper body for elongating the hopper body to reach the shaft. Attached with M5 Allen bolts, the holes in the hopper are in the form of a slot, with an extra aperture for varying the height of the powder deposition container from the build platform surface.

There was a requirement for a mechanism for transmitting the power from the actuator via a shaft to move the powder deposition mechanism in the XY axis. So a shaft was fabricated by using an MS (mild steel) for the connection arm and the box with the help of bearing. The other end of the shaft with a 10mm diameter is coupled to a stepper motors shaft with a 10x5mm flexible coupler.

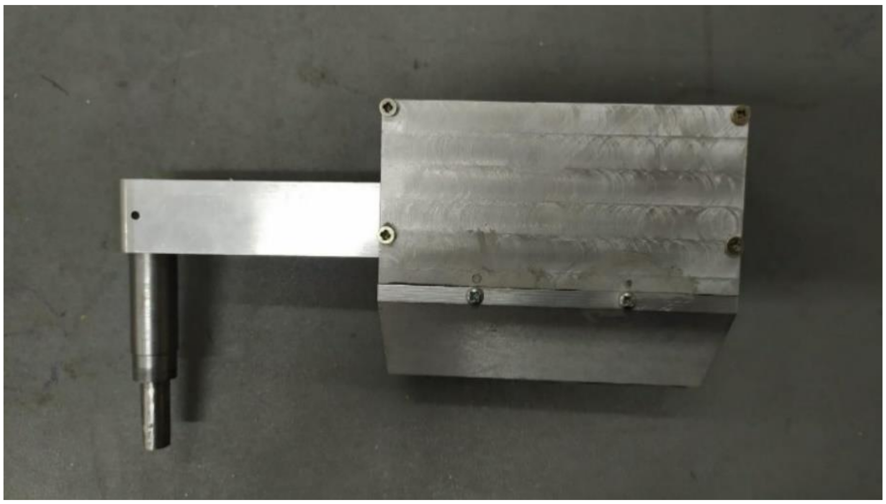

Figure 8 Assembled powder deposition mechanism

Fig. 8 shows the powder deposition mechanism assembly side view, and fig. 9 shows the top view of the machine assembled in the box chamber with attached limit switches on the wall of the chamber for controlling the direction of rotation for the mechanism.

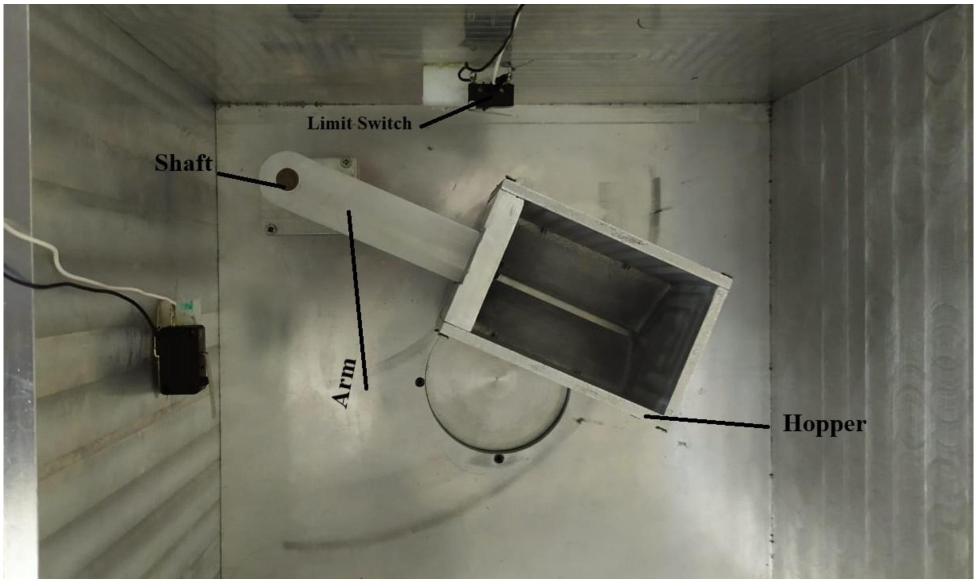

Figure 9 Top view of the powder deposition mechanism assembled inside the SLM chamber

3.1.2. design of the vertical Z-axis mechanism for build platform:

The Z-axis mechanism is responsible for the layer height and the movement of the piston in a cylinder in the vertical direction. This is specially designed to deposit the powder layer of about 10 microns. It contains the cylinder in which will move the piston. Piston's top surface will be the area at which part will be made.

a) Piston

The word layer thickness is mentioned several times in this manuscript, and its importance to the project itself is primary. The mechanism to lift and down the powder bed for the next processing in a layer-by-layer mechanism is controlled by a Z-axis mechanism. It comprises of two parts, a piston mechanism in which a cylindrical piston as a worktable is moved linearly in a cylinder. The hollow cylinder is fixed attached to the box from in the lower plate of the chamber with 90mm of outer diameter and 80mm of inner diameter, and the thickness of 3mm. The cylinder bolted in the upper plate of the mechanism. There is a moving plate designed for the linear vertical stepping of the worktable (piston) up and down. The plate has been made from acrylic for reducing the load that can be bearable for a NEMA17 Stepper motor. The plate is supported by guide rods, so the alignment of the mechanism is maintained, and the piston can be placed over the movable plate for the working of the linear mechanism. The two side plates are fastened to the upper and lower plates of the Z-axis mechanism with Allen bolts, and these two side plates are fixed to support the structure. The complete mechanism of the Z-axis is shown in fig. 10.

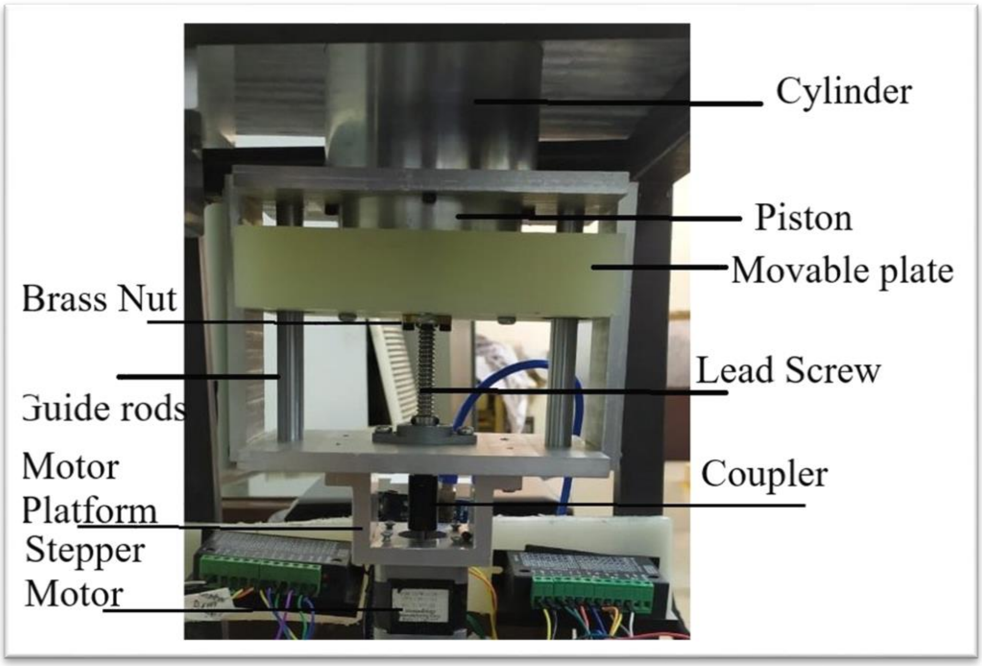

Figure 10 Actual Z-axis mechanism assembled in SLM

b) Lead Screw

The most significant and centrally important part of the Z-axis mechanism, the lead screw, is attached to the linear moving plate of acrylic from one end with the help of a brass nut. Brass nut ensures the lead screw led force is transmitted to the movable plate and ultimately the worktable (piston).

Design consideration for lead screw

- The lead screw used has a number of independent threads on the shaft of the screw; the lead screw selected here has a single start.
- So, in this case, a single start leads screw the same lead and pitch.
- The pitch for the lead screw is equal to 2mm.
- Lead is the distance the nut is advanced along the screw in one revolution.
- As Lead= (No. of starts)(pitch), the lead of this lead screw is 2mm.

So the leadscrew advances 2mm in one revolution of the leadscrew; this helps in controlling the layer thickness and height.

The lead screw is fastened to the lower plate of the mechanism, and below the lower plate, the protruded lead screw is couple to a stepper motor using an 8x5mm shaft coupler for actuation of steps, and the pitch and lead of the lead screw makes sure the control of how much linear vertical motion in worktable takes place relative to the rotating motion of the lead screw.

Figure 11 Lead screw (2mm pitch)(8mm dia) with the brass nut

The other part of the Z-axis mechanism is the motor platform on which the motor is fixed with four screws of M3 and has the side plate to attach with the lower plate of the Z-axis mechanism. This platform structure supports the coupling between the stepper motor and the lead screw; without the platform, the stepper motor will be hanging in the air. For ease and following design for assembly, the part is manufactured based on the design for manufacturing as both motor platforms were required to be fabricated with the minute difference in features requirement according to stepper motors alignment.

3.1.3 Design of the chamber

In selective laser melting, the processing of molten material takes place inside the box, which will be enclosed and filled with inert argon or nitrogen. It is fabricated from Aluminum plates machined to fix into each other to form a boxed chamber. The dimension of the chamber is 320x290x200 mm. In the base plate of the chamber, four-hole of M5 are screwed to the cylinder attached to the upper plate of the Z-axis mechanism. The chamber, according to design, has a top plate with a circular subtraction of part for the placement of the lens of a laser engraver. The top plate will be required to be sealed with material like silicone. The two limit switches are attached to the walls of the chamber for the control of change of direction of rotation for powder deposition mechanism shown in figure of the chamber.

Figure 12 SLM Chamber top view

3.1.4. design of the base frame:

The chamber side plates are placed on the support structure, and the frame is made up of mild steel pipes which hold the load of the whole machine. The Z-axis mechanism is hanging in the open space.

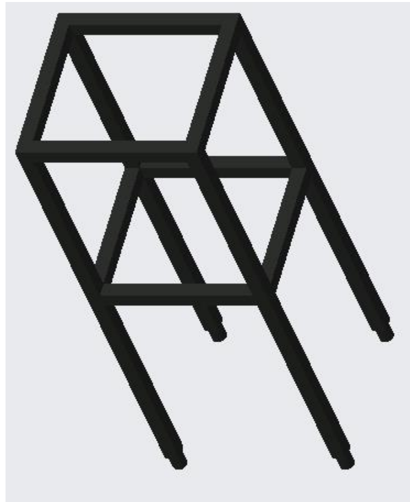

Figure 13 Base Frame CAD Model

The middle bracket of the frame had space to place a sheet to place the control circuitry for the mechanism of SLM. The hole circuitry is mounted on the acrylic sheet platform.

CHAPTER 4 CONTROL

The control system of the SLM machine consists of components. The components are elaborated as follows:

4.1 Actuators

The control is required for the powder deposition mechanism and Z-axis linear vertical motion in the form of steps for the worktable. In the design and development section of SLM, the mechanism was designed, and the actuators were coupled to both the mechanisms. In powder deposition mechanism, a NEMA17 Stepper motor is coupled by 10x5 mm flexible coupling to the shaft of 10mm diameter. The stepper motors used are bi-directional stepper motors, NEMA17 with dimensions of (43 mm × 43 mm). Stepper motor is selected because of its division of a complete rotation into a number of steps. This way, the position of the motor can be controlled precisely, and the requirement for a feedback or position sensor is not needed.

4.2 Controller

Arduino Mega 2560 is used to control the stepper motors, and it is required to control the steps and direction of the shaft and lead screw accordingly. It is a microcontroller board with a microcontroller Atmega2560. It has 54 I/O's with 15 of which can be used as PWM outputs, and these outputs are the one that controls the stepper movement steps and direction by Arduino giving pulse commands. With the help of UART (hardware serial port) communication interface is formed. In this project, the controller is used to serially communicate with the processing IDE, which has the graphical interface for controlling the stepper motors. The Arduino IDE is where the code is sketched and compiled, and the program is uploaded via USB to the Arduino.

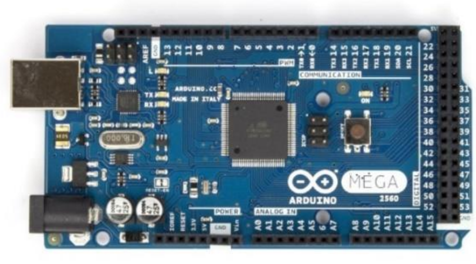

Figure 14 Arduino Mega2560 board

4.3 Motor Driver

Arduino outputs produce a low current logical control signal, so a motor driver is required to run the stepper motor. The motor driver used for this setup is TB6600; the driver can bear a maximum current of 4.5A, which makes it eligible to control larger stepper motors like NEMA23. A motor driver takes the low voltage from the Arduino and amplifies the current pulse so the Stepper motor can be driven. TB6600 is a safe option to use because of its over-current and under-voltage shutdown system, and an alarm led mounted on it gives a signal regarding system interruption. The specifications of the TB6600 are mentioned in table 3.

Operating voltage	9 – 42 V
Max output current	4.5 A per phase, 5.0 A peak[1]
Microstep resolution	full, 1/2, 1/4, 1/8 and 1/16[2]
Protection	Low-voltage shutdown, overheating and over-current protection
Dimensions	96 x 72 x 28/36 mm
Hole spacing	88, ⌀ 5 mm

Table 3 Table for specification of TB6600 motor driver

4.3.1. Microstepping in TB6600

The most important feature of the driver is microstepping, and the stepper motors get the electrical pulse to run a complete step. By microstepping the signal is divided, and the motor is getting signal for less than one step. A stepper motor normally has a step size of 1.8 degrees, which means that for one revolution, 200 steps are required. TB6600 by energizing the coils of the stepper with current intermediate levels makes higher resolution possible to use. Those different modes can be set by switching the dip switches on the driver. Also, the current can be adjusted according to the requirement with the combination of dip switches. The microstep table and current table are mentioned on the driver. We used a 1/8 microstep setting for achieving the required layer thickness for the lead screw-controlled mechanism.

As in the design and development chapter under lead screw design consideration, the lead of the lead screw was discussed. The lead of the lead screw is equal to pitch, which means the lead screw will advance 2mm in one revolution of the lead screw. The lead screw is coupled to a stepper motor.

- Lead Screw Pitch = 2 mm
- Motor Step Angle=1.8^o/Pulse
- No. of Pulses=360^o/1.8^o = 200
- Distance travelled in one pulse = 2mm/200pulses = 0.010 mm = 10 microns

Microstepping provides better resolution and smoother motion of the shaft. The microstep of 1/8 is used, which changes the number of pulses per revolution.

No. of pulses per revolution= 1600 pulse/ revolution (On testing the response of motor with changing steps in code led to the 1500 pulses/rev)

Distance travelled in one pulse= 2mm/1500pulses=0.001mm=1 microns.

Steps for 10 microns will be 10, which will be fed to the Arduino program for single-step vertical movement for the z-axis, and the layer thickness of 10 microns is achieved.

Figure 15 TB6600 Motor Driver

4.3.2. Pin configuration of TB6600

The DIR- and DIR+ pins are for the direct control of the motor and can be controlled by Arduino, and the Dir+ is connected to an output pin of the Arduino board. Similarly, PUL- and

PUL+ are the step control pins, and PUL+ is connected to another Arduino output. The pins below these are attached to the motor according to the combination of coil one and coil 2 of the stepper motor. A power supply of 12V and 10A is attached to the motor driver for powering the stepper motor. Fig. 15 shows the front view of the system, including the labelled components.

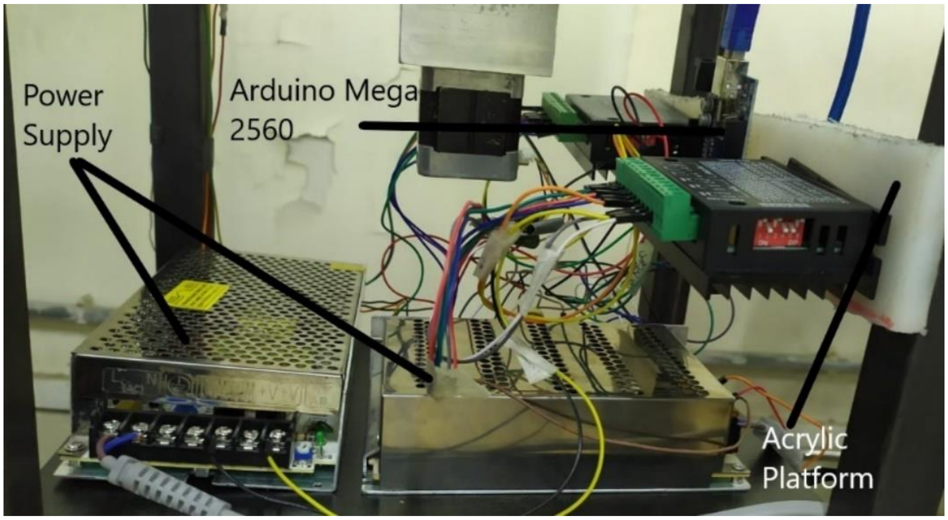

Figure 16 Front view of SLM machine

4.4 Speed Control for powder deposition mechanism

A potentiometer is used to control the speed of the stepper motor coupled to the shaft for controlling arms rotation. The purpose of it is to control the speed with the goal to set it according to the laser's processing time and scanning period. Fig 17 shows the potentiometer, particular motor drivers for specific functions.

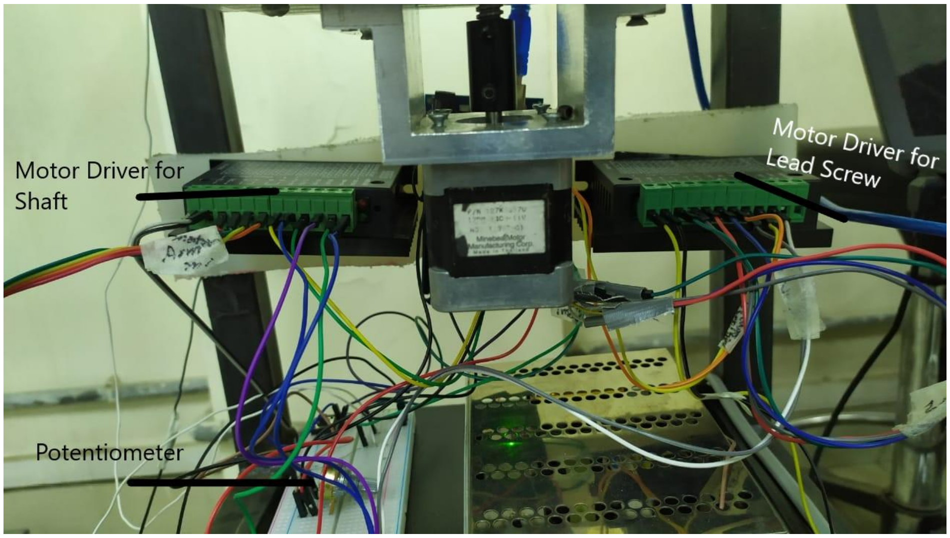

Figure 17 Side View of SLM machine

4.5 Wiring diagram for the control system

The Wiring configuration of the control system for the stepper motors is provided in fig 18 is shown. Where in wire configuration of the interface of the motor is shown, two stepper motors are connected to their particular TB6600 motor drivers. The TB6600's are connected to the specific output pins according to the C language program in Arduino's .ino file. The power supplies are connected to the motor drivers VCC and GND. A potentiometer is also attached to the analog input port of Arduino for controlling the speed of the shaft which rotates the hopper. The PC is connected to the Arduino via USB, which is used to upload the program file and serially communicate to control the system by a graphical user interface made in Processing IDE. Limit switches connected to the defined interrupt pins on Arduino.

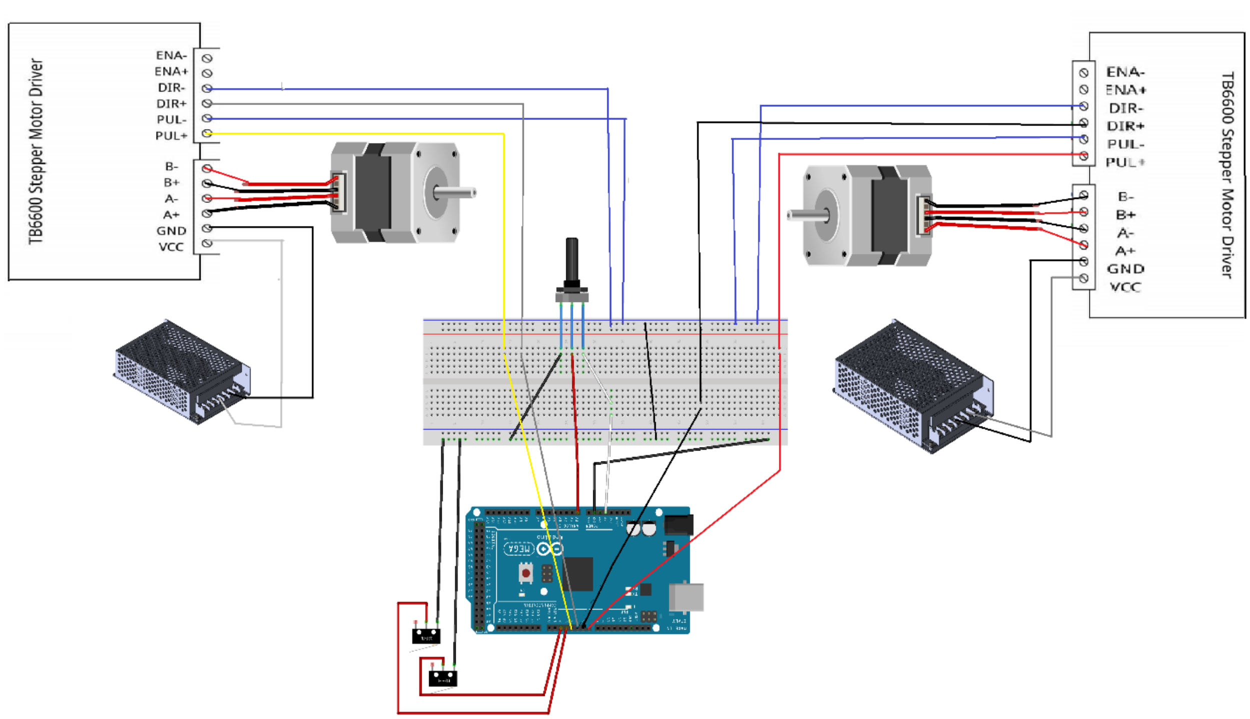

Figure 18 Wiring Configuration of the control system

4.6 GUI for the control of motors

A graphical user interface is developed for the ease of control of stepper motors using a processing IDE.

4.6.1. processing

It is an open-source programming language and tool for the development of applications, and it can serially communicate with the Arduino board. The controlP5 library is used to design a

GUI in a computer environment of processing. The program for processing is written in Java, the default mode. With the help of the ControlP5 library, the draw() loop is used for the making of button interfaces for specific functions. Three buttons are made to control the functions. On pressing a button, a character is transmitted to Arduino via serial communication, which ensures the function is worked.

In our case, an if and else if checks are prompted upon the three buttons. And each button on clicking triggers the function. The powder deposition loop is prompted by clicking "ONESTEP" the whole loop inside it and "NEGSTEPZ" for moving the worktable up for a step. "POSSTSTEPZ" is for moving the worktable down for a step. The GUI interface is shown in fig. 18.

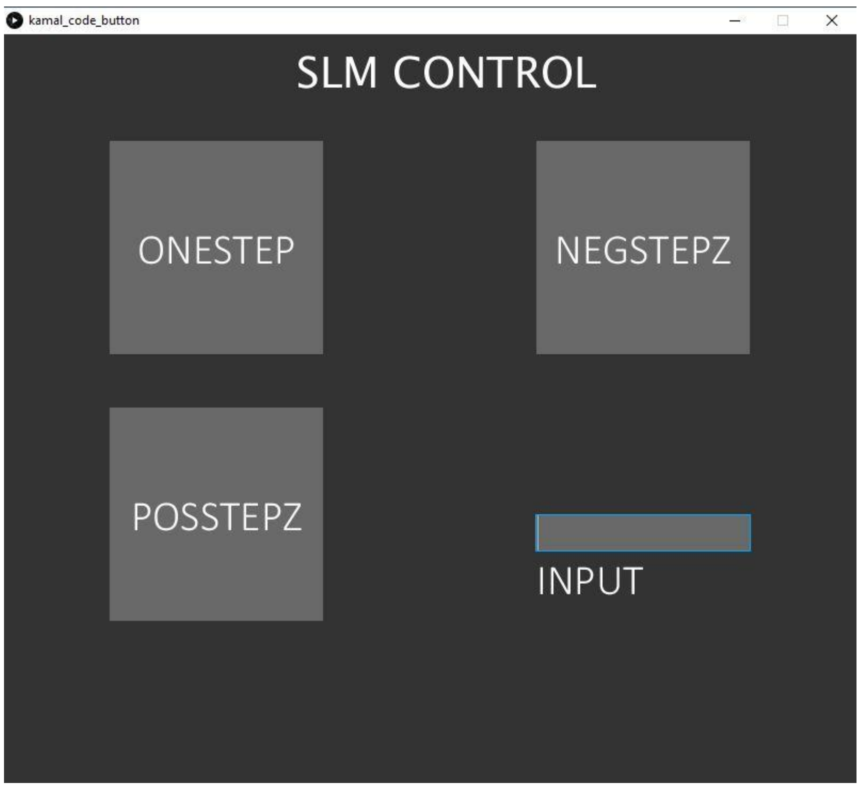

Figure 19 GUI Interface screenshot from PC

4.7 Control System:

4.7.1 For powder deposition mechanism

The pressing of the "ONESTEP" button will communicate Processing with Arduino, and a character which in this code is "r" will be serially sent to Arduino, where the check of if condition will be fulfilled and the loop of one step down of worktable will be made right after the delay of some milliseconds the hopper will be fed with steps for 180 degrees. During these steps, the hopper changes its direction on contacting the lever of the limit switch, triggering the interrupt. On the rotation back to the initial position, the hopper will stop after pressing the other side wall mounted limit switch and stop. This will complete the one-layer of Processing for the SLM. This can be repeated till the formation of the required part. Before thorough experimentation with laser engraving machines, the one-layer mechanism will be suitable for study purposes. In appendix 1, the code of the control for both stepper motors is written.

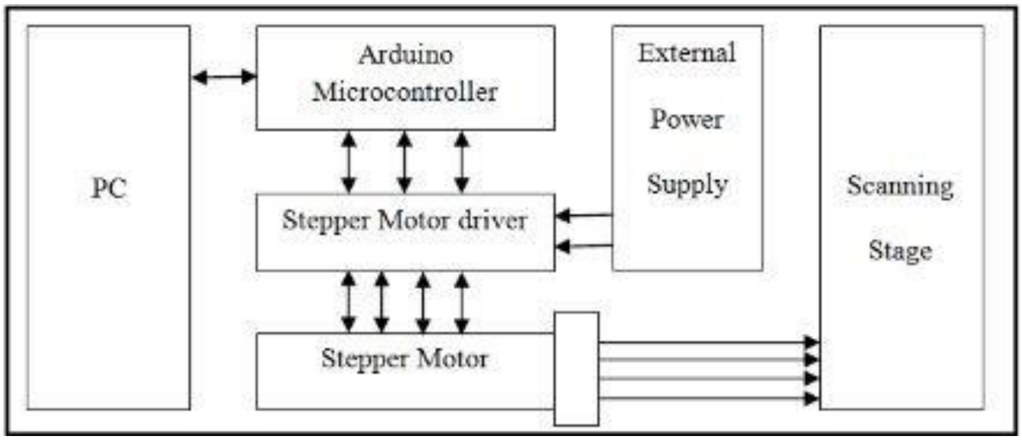

Figure 20 Block diagram for the interface of powder deposition mechanism motor

4.7.2 For worktable control and layer thickness:

The control of the Z-axis provides us with the ability to set the position of the worktable accordingly. Initially, the stepper attached to the shaft is commanded to move before which the worktable takes a step down for a specific height which in fact defines layer thickness. Steps for 10 microns will be 10, which will be used in the Arduino program for single-step vertical movement for the z-axis, and the layer thickness of 10 microns is achieved. For Z-axis step up and step down, two different buttons are set in the GUI to control the vertical movement of the table by moving the lead screw. These functions are required to adjust the worktable and calibrate the worktable after the part is completed. In fig. 21 complete setup of the designed SLM and developed control system is shown.

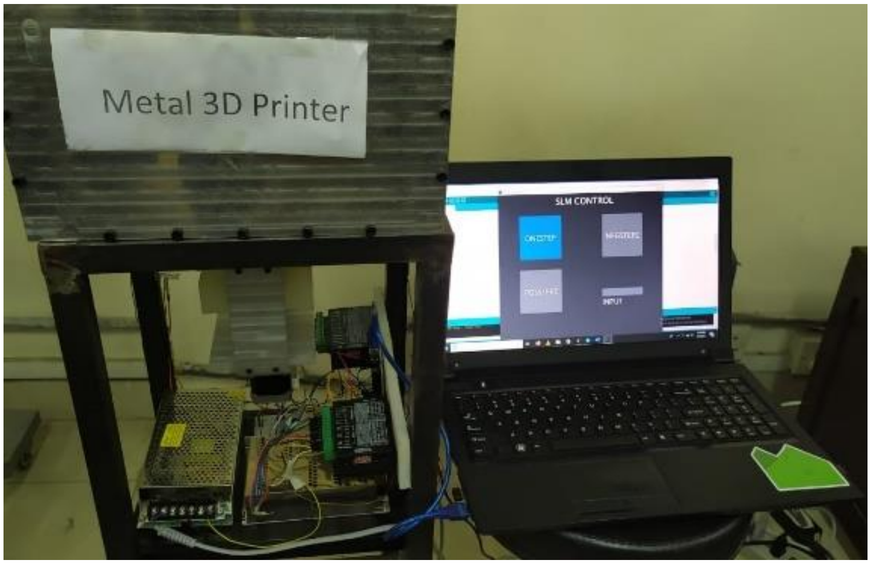

Figure 21 SLM Metal 3D Printer with GUI control

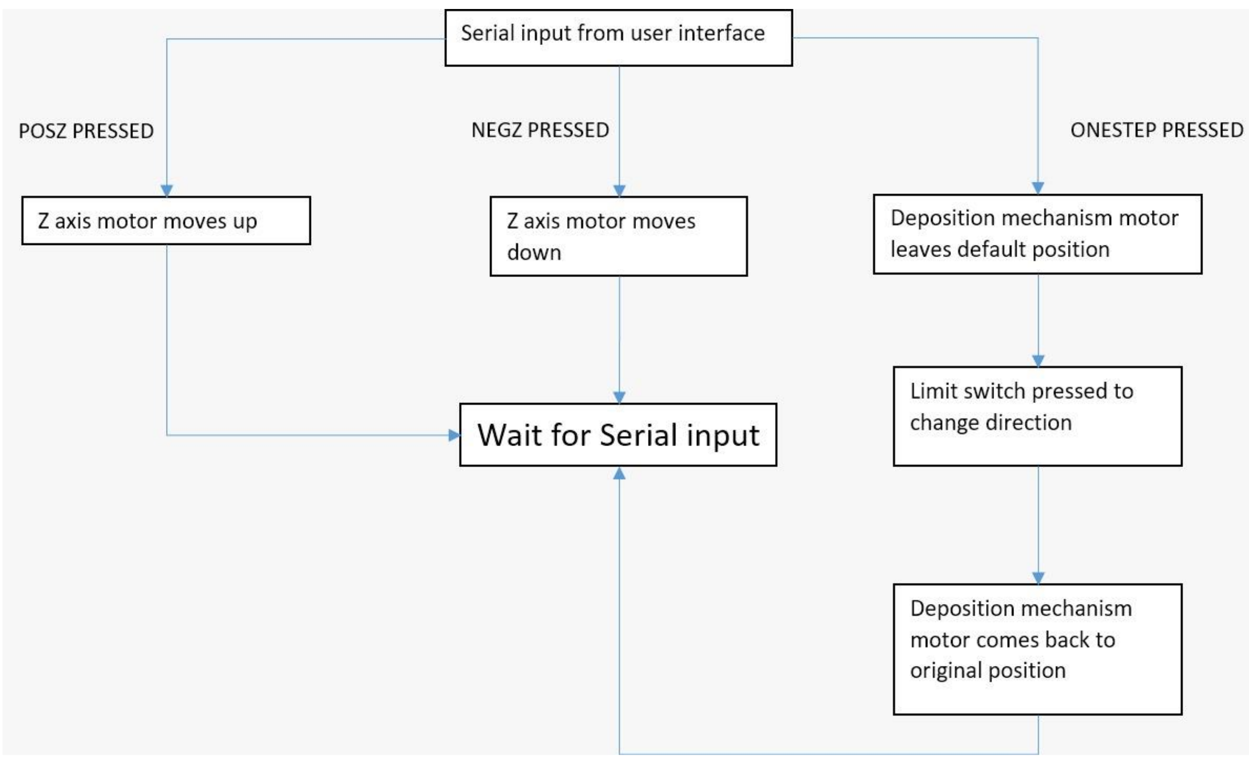

Figure 22 Control flow of the system

CHAPTER 5 CONCLUSION AND FUTURE RECOMMENDATIONS

5.1 Conclusion

The main objective was to design and develop a control system for a selective laser melting machine. The design and development of the SLM machine have been discussed in chapter 3 in detail, with the design process of every assembly discussed. The powder deposition mechanism with the motion of its key part hopper for deposition of metal powder is controlled by the control system. The clockwise and counterclockwise motion of the power mechanism was made sure by using limit switches on the inside walls of the chamber parallel to the hopper's side walls. The process of single-layer deposition and processing on metal powder is controlled in one step is controlled by Arduino Mega board. Also, the Z-axis vertical motion of the worktable attached to a lead screw is controlled. The layer thickness has been programmed for 10 microns. As the motion of worktable in pulses of stepper motor is translated accordingly. We used microstepping by a microstep motor driver for better resolution and smooth functioning of stepper motor. A GUI was developed for controlling the functions of the motor with ease of control.

5.2 Recommendations for future work

The SLM machine is presently not able to print a metal part, and the experimentation on a metal powder of 10 microns particle size is not yet done. With the following recommendations, the machine can be set to work for experimentation and further along with the phase, a working prototype will be available.

- Most importantly, a feedback mechanism for the control of worktable height is required. That will confirm the layer thickness for the deposited powder on the worktable of SLM with respect to the control system's input. Positional feedback sensors like displacement sensors can be used. For precise resolution in microns can be calculated by laser interferometers or linear encoders.
- The SLM process requires an environment with the least oxygen presence for reduction of oxidation during the process. Complete sealing of the chamber is required.
- An oxygen sensor for the monitoring of oxygen levels inside the chamber is required.

- For the observation of the experiment inside the SLM chamber, a camera is required to study the process parameters during the processing of metal, like melt pool formation.
- For further enhancing the process of SLM, pre-heating of the chamber or the powder bed of the SLM machine can reduce residual stresses with higher mechanical properties and reduced energy consumption. A mechanism for pre-heating should be designed to enhance the efficiency of the processing of the machine.

APPPENDIX A

ARDUINO CODE FOR STEPPER MOTORS:

```
#define dirPin 4              // ALL THE PINS ARE DEFINED
#define stepPin 5  // stepPin +dirPin are for powder deposition mechanism stepper motor
#define dirZax  6
#define stepZax 7   // For Z-axis stepper motor
#define stepsPerRevolution 750 //Steps defined for shaft 180 degrees
#define spr 10 //Steps defined for z-axis motor //original was 1600
//interrupt code
const byte interruptPinP = 21;
const byte interruptPinR = 2; //Interrupt pin for cw rotation
const byte interruptPinL = 3;// Interrupt pin for ccw rotation
//volatile byte state = LOW;
int pinR = 7;
int potPin = A0;  // analog input from potentiometer to arduino
int val;
int delayValue;
int switchvalue = 0;
int number;
void setup() {                          // Setting up for defining the role of I/O's to pins
pinMode(stepPin, OUTPUT);
  pinMode(dirPin, OUTPUT);
  pinMode(pinR, INPUT);
  pinMode(led, OUTPUT);
  pinMode(stepZax, OUTPUT);
  pinMode(dirZax, OUTPUT);
  // Set the spinning direction CW/CCW:
  digitalWrite(dirZax, HIGH );
  digitalWrite(dirPin, HIGH );
  Serial.begin(9600);
  pinMode(interruptPinR, INPUT_PULLUP);
```

```
  attachInterrupt(digitalPinToInterrupt(interruptPinR), moveleft, RISING);
  pinMode(interruptPinL, INPUT_PULLUP);
  attachInterrupt(digitalPinToInterrupt(interruptPinL), moveright,RISING);

void loop() {

if (Serial.available()>0) { // If data is available to read,
    char val = Serial.read(); // read it and store it in val
    delay(40);
  if(val == 'r') //if we get a r via processing serially (loop for complete layer step will run)
    {
      val = analogRead(potPin);
      delayValue = (val*2)+500;
  // Spin the stepper motor 1 revolution slowly:
       for (int i = 0; i < spr; i++) {
    // These four lines result in 1 step:

          digitalWrite(stepZax, HIGH);
          delayMicroseconds(50);
          digitalWrite(stepZax, LOW);
          delayMicroseconds(50);}
          delay (40);
       // Set the spinning direction clockwise:

      for (int i = 0; i < stepsPerRevolution; i++) {
    // code for 1 step
    digitalWrite(stepPin, HIGH);
    delayMicroseconds(delayValue);
    digitalWrite(stepPin, LOW);
    delayMicroseconds(delayValue);}
    //Serial.println(delayValue);
```

```
  }

 else if(val == 'y') //if we get a y (for Z-axis down)
      {
        for (int i = 0; i < spr; i++) {

  // These four lines result in 1 step:
      digitalWrite(dirZax, LOW );
      digitalWrite(stepZax, HIGH);
      delayMicroseconds(50);
      digitalWrite(stepZax, LOW);
      delayMicroseconds(50);}
      delay (40);
 }
    else if(val == 'x') //if we get a x(for Z-axis down)
      {
        for (int i = 0; i < spr; i++) {

  // These four lines result in 1 step:
      digitalWrite(dirZax, HIGH );
      digitalWrite(stepZax, HIGH);
      delayMicroseconds(50);
      digitalWrite(stepZax, LOW);
      delayMicroseconds(50);}
      delay (40);
}
  }
}
void moveleft() {// On limit switch interrupt will change the direction of shaft coupled motor
 digitalWrite(dirPin, HIGH);
 delayMicroseconds(100);
```

```
}

void moveright() {
  digitalWrite(dirPin, LOW);
  delayMicroseconds(100);
  }
```

APPENDIX B

PROCESSING CODE:

```
import controlP5.*; //import gui library
import processing.serial.*;
Serial port;
ControlP5 Program; //create control p5 object
String textValue = "";
PFont font;
String t;
void setup(){
  size(800,800);

  printArray(Serial.list());
  port = new Serial(this, "COM7", 9600);
  Program = new ControlP5(this); // create Program instance
 font = createFont("calibri light", 40);

 Program.addTextfield("input")
   .setPosition(500,450)
   .setSize(200,35)
   .setFont(font)
   .setFocus(true)
   .setColor(color(255,0,0))
   ;

 Program.addButton("OneStep")     // create 1 step button
     .setPosition(100,100)
     .setSize(200,200)
     .setFont(font);
     Program.setColorBackground( color( 105,105,105 ) );
```

```
  Program.addButton("NegStepZ")      // create 2 step button for Z-axis up
       .setPosition(500,100)
       .setSize(200,200)
       .setFont(font);
  Program.addButton("PosStepZ")      // create  step button for Z-axis down
       .setPosition(100,350)
       .setSize(200,200)
       .setFont(font);

}

void draw(){    // this function is for the setting of the GUI in graphics
 background(51);
 textSize(40);
 text("SLM CONTROL",275,50);
 text(Program.get(Textfield.class,"input").getText(), 360,130);
 text(textValue, 360,180);
}

void OneStep(){ // functions for the buttons to send serial input to the Arduino for specific
loop
port.write('r');     // value serially sent to arduino
}
void NegStepZ(){
port.write('y');
}
void PosStepZ(){
port.write('x');
}
```

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